Indoor Environmental Technology

an evaluation of the research activities from 1989 to 1994

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INDOOR ENVIRONMENTAL TECHNOLOGY

AALBORG UNIVERSITY

An Evaluation of the Research Activities from 1989 to 1994

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Indoor Environmental Technology

Aalborg University

An Evaluation of the Research Activities from 1989 to 1994

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Preface

This report is the outcome of a research evaluation which started in the autumn 1994. The evaluation of the research unit *Indoor Environmental Technology* was requested by the Faculty of Science and Technology at Aalborg University. The guidelines from the Faculty of Science and Technology specify that the main purposes of the research evaluation are to:

- Assess whether there is a satisfactory agreement between allocated internal and external resources and the research accomplished
- Assess whether there is a reasonable agreement between the objects of the unit regarding future research and the research accomplished
- Advise the unit with regard to future efforts and organization of the research

All members of the Indoor Environmental Group have contributed to the contents of the report. The research accomplished and the plans for future research have been discussed at a number of meetings during 1995. The external members of the evaluation committee *Professor P. O. Fanger, Technical University of Denmark* and *Dr. Alfred Moser, Swiss Federal Institute of Technology, Zurich, Switzerland* visited the department in November 1995 to discuss the research evaluation with the members of the group.

Chapter 1 presents the framework for the evaluation process including general guidelines from the Faculty of Science and Technology. Chapter 2 presents the historical background of the Indoor Environmental Group and the resources allocated to the group. Chapter 3 describes the research carried out during the evaluation period and the group's own evaluation of the research accomplished. Chapter 4 describes other activities related to research and information about the members of the research group. Chapter 5 contains a list of publications produced during the evaluation period. Chapter 6 contains the evaluation report written by the external members of the evaluation committee.

December 1995
Kjeld Svidt

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Chapter 1
Framework for the evaluation of indoor environmental technology

1.1 Introduction

The research unit for indoor environmental technology is one out of 18 research planning units at The Faculty of Technology and Science at Aalborg University. At regular intervals the Faculty works out a strategic plan regarding the allocation of university resources to each of these units. Such plans were made in 1986 and 1989.

To stimulate the research activities, a scheme for systematic and recurrent evaluation of the progress and results of the research units was initiated in 1990. In 1993 the Faculty of Technology and Science decided to perform an evaluation of four research units including the research planning unit for indoor environmental technology.

The Faculty has allocated resources corresponding to half a man-year to perform the work. The research evaluation is carried out according to the general guidelines described later in this chapter.

The faculty has specified that the evaluation report should include:

- The faculty framework for the evaluation, including the long-term research plans presented by the research unit in 1986 and 1989
- The resources allocated to the research unit from the University and from external financing
- A presentation of the research performed up to date
- A report from the evaluation committee

1.2 Long-term research plan 1986

In 1986 the Faculty completed a long-term research plan for all its research planning units. At that time the planning unit for indoor environmental technology presented its structure as follows:

The research planning unit comprises conditions for and methods to create a healthy indoor environment with attention to the lowest possible energy consumption. The conditions for a healthy indoor environment comprise the needs of humans and animals in the building. The demands include acceptable levels of air velocities in the occupied zone and a good indoor air quality comprising the level of particulate and gaseous contaminants.

Methods to create a healthy indoor environment include the choice of materials and composition of the building envelope plus the choice of appropriate building services, so that an optimal indoor environment and energy consumption are obtained in each individual case. The major issue of the research unit is the interaction between the building, its use and the installations.

The fields covered by the research unit include utilization of passive energy sources, low energy installations, ventilation equipment, air conditioning, heating and cooling installations, water and sanitary installations, as well as questions relating to calculation, measuring and control of the indoor environment and the energy consumption in buildings.

Two subjects have been adopted as fields of special effort:

- *Air Flow and Contaminant Distribution in Ventilated Rooms*
- *Models and Control Strategies for Energy Consumption in Buildings.*

***"Air Flow and Contaminant Distribution in Ventilated Rooms"** has been chosen in consequence of the increasing indoor environmental problems demonstrated in recent years, and because the Danish and international research efforts within this field are remarkably small. Due to the fact that most indoor environmental problems can be solved within this domain research in this field must be accelerated as much as possible.*

***"Models and Control Strategies for Energy Consumption in Buildings"** has been chosen being conscious of a controlled use of energy resources. Knowledge* *of the function of single components and complete systems under a dynamic load should be continuously improved. Furthermore control strategies must be developed and tested. On the long view this knowledge will be part of the basis for decisions, which will be integrated in expert systems. Parallelly this knowledge will create a basis for a reexamination of the design principles and the system layout of HVAC installations considering that the design loads are dynamic.*

In addition, the group plans to initiate research within the field: ***Indoor Environment Contamination****. This field has been chosen because solving indoor environmental problems by controlling the air flow and the contaminant distribution in ventilated rooms is only partially possible. A fundamental solution of the indoor environmental problems requires an investigation of the indoor environmental contamination in existing buildings, to come up with solutions that, among other things, will be based on the knowledge obtained in the field: Air flow and Contaminant distribution. These two fields will supplement each other with important fundamental knowledge.*

The choice of the subjects of special effort, mentioned above, should be regarded as a natural continuation of the building up of the indoor environmental laboratory that has taken place during recent years. This is a development taking place parallelly with simultaneous changes in the teaching carried out by the research unit.

1.3 Long-term research plan 1989

The Faculty completed again in 1989 a long-term research plan for all its research planning units. The research unit for indoor environmental technology presented its structure as follows:

The research unit for indoor environmental technology constitutes a discipline based on the requirements of the human body for appropriate physical surroundings, i.e. healthy and comfortable surroundings. In special cases the needs of other living creatures are also dealt with.

Methods to create a healthy indoor environment include the choice of materials and composition of the building envelope plus the choice of appropriate building installation. In this way an optimal indoor environment and energy consumption *are obtained in each individual case. The interaction between the building, its use and the installations is the most important issue of the research unit.*

Since indoor environmental technology is facing parameters with many physical dimensions, several basic scientific disciplines are attached to this research unit. Examples are: Fluid dynamics, thermodynamics, heat transfer and radiation as well as the physiology and chemistry of the human body. As Indoor Environmental Technology is a quantity of numerous parameters, experimental work on the indoor environment involves extensive use of measuring equipment in large-scale experiments. This can be large geometrical dimensions in full-scale test rooms reproducing the conditions in residential or industrial premises, or it can be experiments involving persons and field experiments with large dimensions in time and number. Today, electronic data processing is essential in the treatment of experimental results as well as in the development of theoretical models within the indoor environmental technology.

Since the research field of indoor environmental technology consists of an interaction between several basic scientific disciplines, it cannot be handled properly within the framework of the single basic scientific disciplines. On the other hand, it is not expedient that one research unit tries to cover the full research field, so the research unit has decided to focus on a few selected areas within the research field.

For the years 1989 to 1993 the research unit has chosen to continue the work with two of the previous subjects, which were chosen to receive a special effort:

- *Control Strategies for Energy Consumption in Buildings*
- *Air Flow and Contaminant Distribution in Rooms*

Furthermore, one of the previous subjects has been reformulated hence the third subject to receive special effort during the years 1989 to 1993 will be:

- *The influence of the outdoor climate and external contaminant sources on the indoor environment in buildings*

Control Strategies for Energy Consumption in Buildings *has been chosen being conscious of a controlled use of energy resources. Knowledge of the function of single components and for complete systems under a dynamic load, should be continuously improved. Furthermore, control strategies must be developed and* *tested. On the long view this knowledge will be part of the basis for decisions which will be integrated into expert systems. Parallelly this knowledge will be the basis for a reexamination of the design principles and the system layout of HVAC installations considering that the design loads are dynamic.*

Thus Control Strategies for Energy Consumption in Buildings will have a substantial significance in connection with the increasing use of building energy management systems (BEMS). The market for building energy management systems is growing quickly (10 - 20% per year) and there is a great need for fundamental knowledge of control strategies that can ensure real energy savings.

The work on this subject is based on computerized models which are modified according to the knowledge obtained from the research field: Air distribution in rooms. Furthermore the research includes full-scale laboratory experiments. The research group behind this field of effort takes part as a Danish observer in a project within the International Energy Agency (IEA). This project deals with the interaction between the rooms in a building, which is closely related to the present research field.

***Air Flow and Contaminant Distribution in Rooms** has been chosen on account of the increasing indoor environmental problems demonstrated in recent years. Due to the fact that most indoor environmental problems can be solved within this domain research in this field must be accelerated as much as possible.*

Contaminant distribution and control of the atmospheric climate at workplaces are very important to the common well-being of the occupants, and especially as to serious problems such as injuries caused by inhalation of dangerous gasses and particles.

***Air Flow and Contaminant Distribution in Rooms** is a field of immediate importance. The International Energy Agency has chosen **Air Flow Patterns** as an international collaboration project, and the research group represents the Danish contribution to this work. In May 1989 the research group will arrange a symposium for all the participating countries.*

***The influence of the outdoor climate and external contaminant sources on the indoor environment** in buildings is the newest research field within the research unit, and it is a natural consequence of the two other fields of effort. This field focuses on the interaction between the outdoor climate and the building structure.*

It will among other things deal with optimal building constructions under special climatic conditions, e.g. locations with high wind loads or locations with a climate unusual to Danish building.

This field of effort will be dealt with during the full period from 1989 to 1993, but only with a limited effort in the first part of the period, e.g. literature studies and computer simulations. Measurement equipment for a more intensive effort will be purchased in the latter part of the period.

1.4 Allocated resources from the university

The table below shows the resources, man-years, that Aalborg University allocated to the group during the evaluation period. **Staff** indicates the number of persons allocated to the group. The staff has only a certain percentage of their time for research. **Research time** is the sum of research hours for each category converted to research man-years.

Staff, man-years	1989	1990	1991	1992	1993	1994
Full professors	1	1	1	1	1	1
Associate professors	4	4	4	4	4	4
Assistant professors	0.5	1	1.4	1.6	1	0.5
PhD students	2.5	2	0.6	0.4	1.3	1.4
Research time, man-years						
Full, associate and assistant professors	2.0	2.1	2.4	3.1	2.3	1.7
PhD students	2.0	1.6	0.5	0.3	1.1	1.1
Total research time	4.0	3.7	2.9	3.4	3.4	2.8
Non-academic research assistance	1.9	1.6	1.2	1.4	1.3	1.3

Table 1.1 Allocated resources from the university.

1.5 General guidelines for the research evaluation

The evaluation is to be performed for each planning unit separately and is to include the work of the whole unit accomplished since the previous evaluation.

Normally, evaluation of the individual planning unit is performed every fifth year. The department is to stipulate the specific time for the evaluation.

The evaluation is to be performed by an evaluation committee, normally consisting of three persons, of whom maximally one should be a department representative and at least one should be from outside the university. The department representative has no voting rights in the committee. The committee is appointed by the Faculty Board based on recommendations from the department.

The evaluation comprises:

- Published research results
- Other research results (that are not published in the traditional way but are brought to the knowledge of private enterprises, public authorities or other groups of society, results conveyed via curricula or presented untraditionally and results in publication etc.)
- Current research
- Other research activities (international research cooperation, participation in scientific congresses, conferences, symposia, editorial and referee activities, participation in dissertation and professorship committees, etc.)
- Research cooperation

The evaluation is to:

- Assess whether there is a satisfactory agreement between allocated internal and external resources and the research accomplished
- Assess whether there is a reasonable agreement between the objects of the unit regarding future research (as specified in the long-term research plan of the Faculty) and the research accomplished
- Advise the unit with regard to future efforts and organization of the research

The evaluation committee prepares a preliminary evaluation which will be discussed with the staff of the research unit. In the light of this, the final report will be prepared and submitted to the Faculty with comments from the research unit and the department.

The department is to perform its own research evaluation within these general guidelines in order to comply with the requests and activities of the department in the best possible way.

Chapter 2
The indoor environmental group

2.1 Historical background

Aalborg University was founded in 1974. At that time the Indoor Environmental Group consisted of 5 teachers from a former engineering school who had no time for research, no laboratories and no measuring equipment at their disposal. The Indoor Environmental Group became a part of the Department of Building Technology and Structural Engineering, which at that time was located in an old public school in Aalborg. In spite of the modest research possibilities, research and development activities were initiated and the first simple laboratory was build in 1975.

Later the Danish Ministry of Education approved Aalborg University as a research institution and during the following years the first measuring equipment was purchased, mainly for grants from The Danish Technical Research Council (STVF). In 1982 the department moved to its present location where the building up of new laboratories started in 1983. Two full-scale test rooms were completed

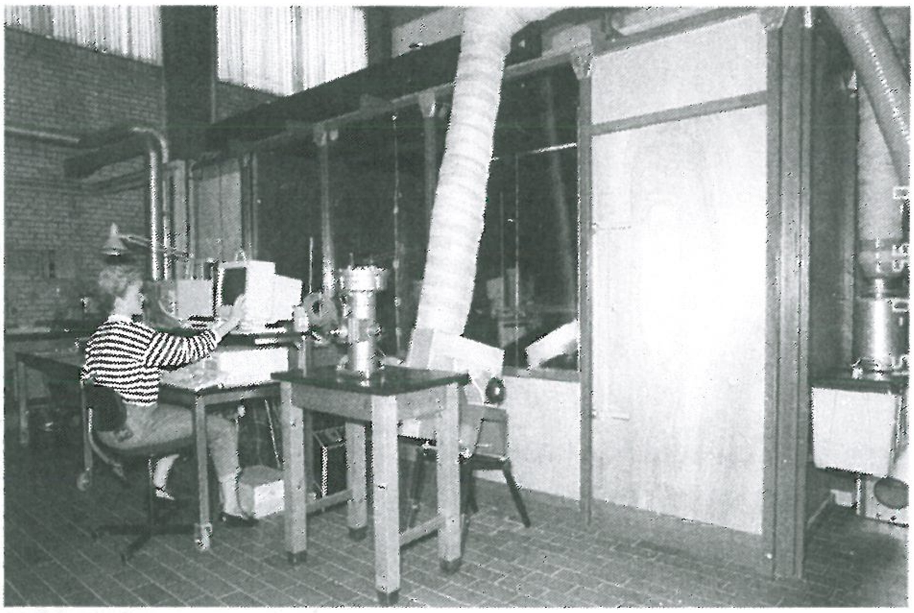

Figure 2.1 Full-scale test room for air flow experiments. The room is 5.4 m long, 3.6 m wide and 2.4 m high. This room was replaced in 1994.

in 1984 (figure 2.1 and 2.3). A larger full-scale test room with an adjustable ceiling was built in 1988 (figure 2.2). The new and larger test room opened the way for full-scale experiments with air flow and contaminant distribution in ventilated rooms. In addition, it gave a substantial improvement of the possibilities of examining local flows in calm surroundings.

Parallel to the development of full-scale test rooms grants for the purchase of advanced measuring equipment were obtained. The main emphasis has been concentrated on equipment for measuring indoor air temperature, air velocity and tracer gas concentrations. The most important equipment is data loggers for measuring air temperature in multiple points by means of thermocouples, equipment for measuring air velocities in several points simultaneously and gas analysers for measuring tracer gas concentrations in a number of points.

In 1986 Peter V. Nielsen was appointed professor in Indoor Environmental Technology. Consequently, the research on air distribution in rooms was given a high priority. Peter V. Nielsen had 15 years of experience in the use of Computational Fluid Dynamics for the calculation of room air distribution, so it was natural to apply this research method in addition to the full-scale laboratory measurements.

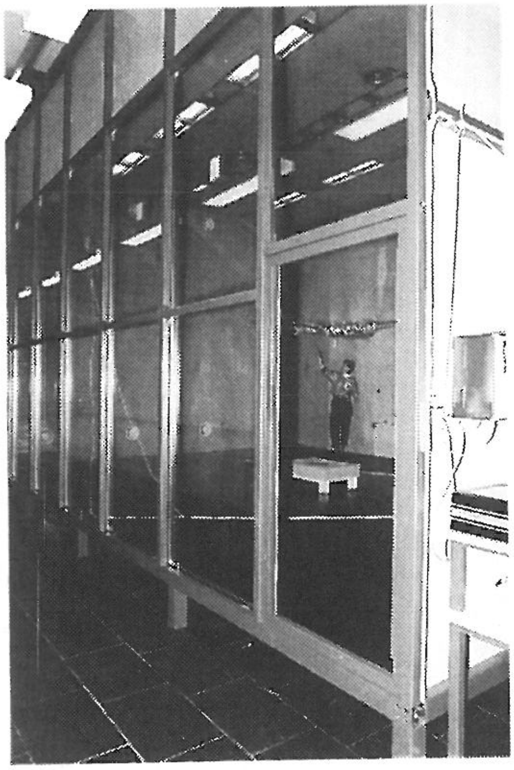

Figure 2.2 Full-scale test room built in 1988. The room is used for experiments with air flow and contaminant distribution. The room is 8 m long, 6 m wide and the room height can be adjusted from 2.4 to 4.6 m.

2.2 Resources allocated to the group

Staff

The resources allocated to the Indoor Environmental Group in the evaluation period 1989-1994 are presented in table 2.1. The resources are divided into staff-years and research-years. Five full and associate professors have been allocated to the group throughout the evaluation period, while the number of assistant professors varied between 0.5 and 1.5. The number of research scholars decreased from 2.5 in 1989 to approximately 0.5 in 1991 and 1992. During the last two years the number has increased again.

Although the number of staff has been almost constant through the evaluation period the research time has been decreasing mainly because of an increase of educational and administrative tasks. The total research time allocated from Aalborg University was about 20 man-years in the evaluation period.

Research-years funded externally have been increasing during the evaluation period from 1.6 man-years in 1989 to 3.3 man-years in 1993 and 1994. The total number of externally funded research-years was about 16.

Grants

The major grants obtained in the evaluation period 1989-1994 and future grants known by December 1994 are listed in table 2.2. The Indoor Environmental Group has obtained about 4 million DKK from external funding, primarily from the Government through the Danish Energy Agency and Danish Technical Research Council. Together with private funding the Faculty of Technology and Science has contributed funds for equipment in the continuous building up of the Indoor Environmental Laboratory. The external funding has been increased during the evaluation period from about 0.3 million DKK per year in 1989 to about 1.1 million DKK per year in 1994. The expansion of external funding is expected to continue.

University staff	1989	1990	1991	1992	1993	1994
Full professors	1.0	1.0	1.0	1.0	1.0	1.0
Associate professors	4.0	4.0	4.0	4.0	4.0	4.0
Assistant professors	0.5	1.0	1.4	1.6	1.0	0.5
PhD students	2.5	2.0	0.6	0.4	1.3	1.4
Staff financed from external funding						
Associate professors						0.8
Assistant professors				0.3	1.0	0.3
PhD students	1.0	1.4	2.0	1.0	0.6	1.0
Staff from other institutions with affiliation to the group						
Assistant professors			0.3	1.0	1.0	0.8
PhD students	1.0	1.0	1.0	1.0	1.0	0.7
Research time						
Full, associate and assistant professors (a)	2.0	2.1	2.4	3.1	2.3	1.7
Research scholars (b)	2.0	1.6	0.5	0.3	1.1	1.1
Research-years, university (a+b)	4.0	3.7	2.9	3.4	3.4	2.8
Research-years, external (c)	1.6	1.9	2.7	2.9	3.3	3.3
Research-years, total (a+b+c)	5.6	5.6	5.6	6.3	6.7	6.1

Table 2.1. Resources allocated to the Indoor Environmental Group during the evaluation period 1989 - 1994. The staff and research time are given in man-years.

	1989	1990	1991	1992	1993	1994	1995	1996	1997
The Faculty of Technology and Science	172								
Danish Energy Agency, IEA Annex 20	30	35	35						
Danish Energy Agency, IEA Annex 20	125	270	255						
The Rockwool Prize		250							
Danish Energy Agency			100	100	100				
Danish Research Academy			100	100	100				
The Veltherm Fund, Thermal Manikin				350					
The Faculty of Technology and Science, Instruments				350					
Danish Energy Agency, IEA Annex 26					350	390	400	390	
Danish Technical Research Council, IEA Annex 26					200				
Danish Technical Research Council, Healthy Buildings					103	705	690	500	500
Danish Energy Agency							225	225	
Danish Agricultural and Veterinary Res. Council							100	400	400
Total	327	555	490	900	853	1095	1415	1515	900

Table 2.2 A survey of major grants received during the evaluation period 1989 - 1994 and future grants known by December 1994 (1000 DKK).

2.3. Laboratories and equipment

Laboratories

In section 2.1 it is explained how the Indoor Environmental Laboratory was developed during the years 1974-1989. This section describes the development during the evaluation period 1989-1994 and the status at the end of 1994.

The greatest asset in the Indoor Environmental Laboratory is the full-scale test rooms for the examination of air flow and tracer gas distribution in rooms. From the beginning the Indoor Environmental Group focused on the investigation of isothermal flow in empty rooms, however, during recent years the research has been extended to non-isothermal flow in empty rooms or in furnished and occupied rooms.

Figure 2.3 Full-scale test room with an internal wall dividing the room into a warm and a cold section. The cold section can be cooled down to -10 °C. This room has mainly been used for the investigation of dynamic heat transfer and downdraught from cold windows.

Since the uninsulated test rooms do not give satisfactory conditions for the examination of non-isothermal flow, the first test room (figure 2.1) has been replaced with a new highly insulated test room (figure 2.4). At the end of 1994 the Indoor Environmental Laboratory consists of three full-scale test rooms. The rooms are built to the philosophy that it must be easy to modify the set-up according to the needs in each individual project. In that way it is for example easy to change the position and type of air inlet and outlet device; the room geometry can be changed by temporary internal walls etc.

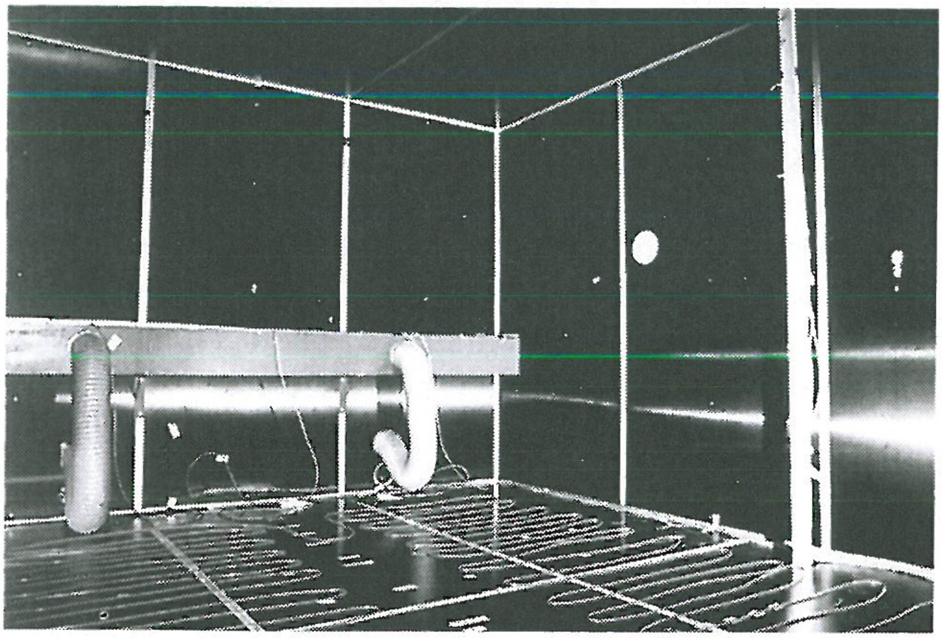

Figure 2.4 Interior from the highly insulated test room. The room is used for the examination of non-isothermal flow in ventilated rooms with and without furniture and persons. This picture shows an arrangement with a two-dimensional slot inlet and an electrical heat load on the floor. The room is 5.4 m long, 3.6 m wide and 2.5 m high.

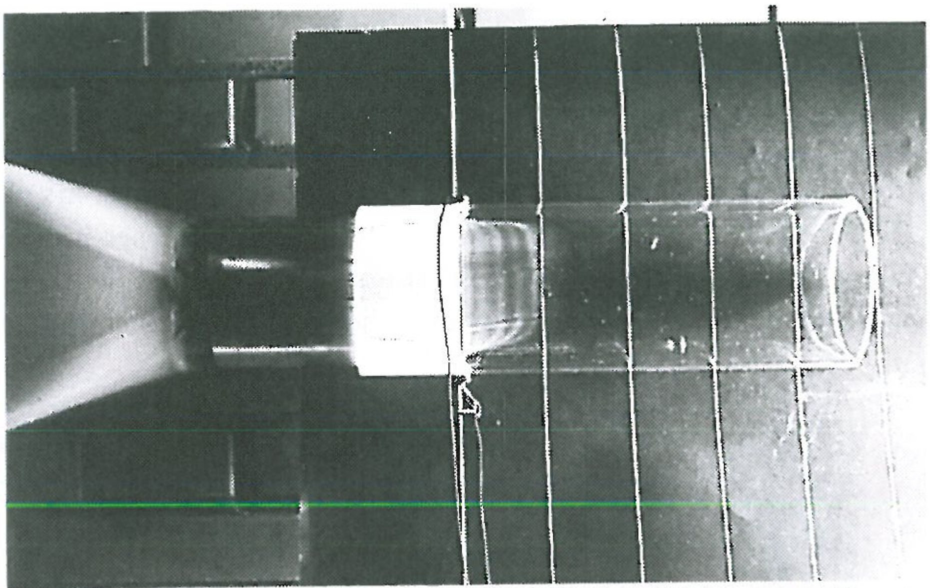

Figure 2.5 Smoke visualization of the velocity profiles in front of a wind tunnel for the calibration of anemometers. This picture shows a calibration of the wind tunnel itself. The air velocity is determined by photographing the smoke movement with four pictures per second.

The Indoor Environmental Group has developed a large part of the calibration equipment used in the laboratory. Figure 2.5 shows a wind tunnel for the calibration of anemometers. The wind tunnel can be rotated to produce upward or downward air flow as well as horizontal air flow. This is an important feature for the calibration of anemometers at low air velocities where the natural convection around a heated velocity sensor can affect the local air flow significantly.

In addition to the full-scale test rooms that are used for several different projects, a number of temporary arrangements have been built for individual projects. Figures 2.6 and 2.7 show examples of such equipment.

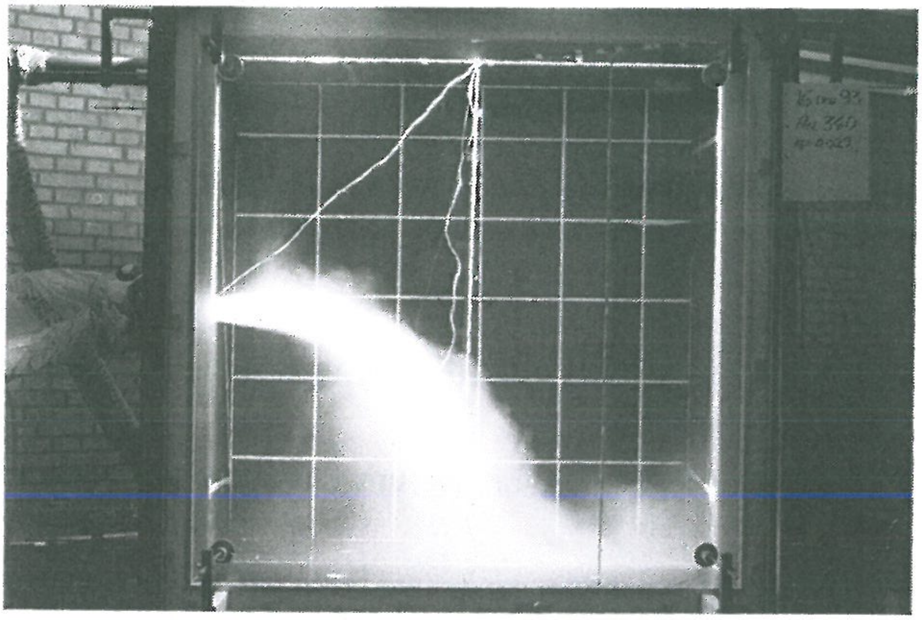

Figure 2.6 Smoke visualization of the air flow pattern in a scale model with buoyancy-affected flow.

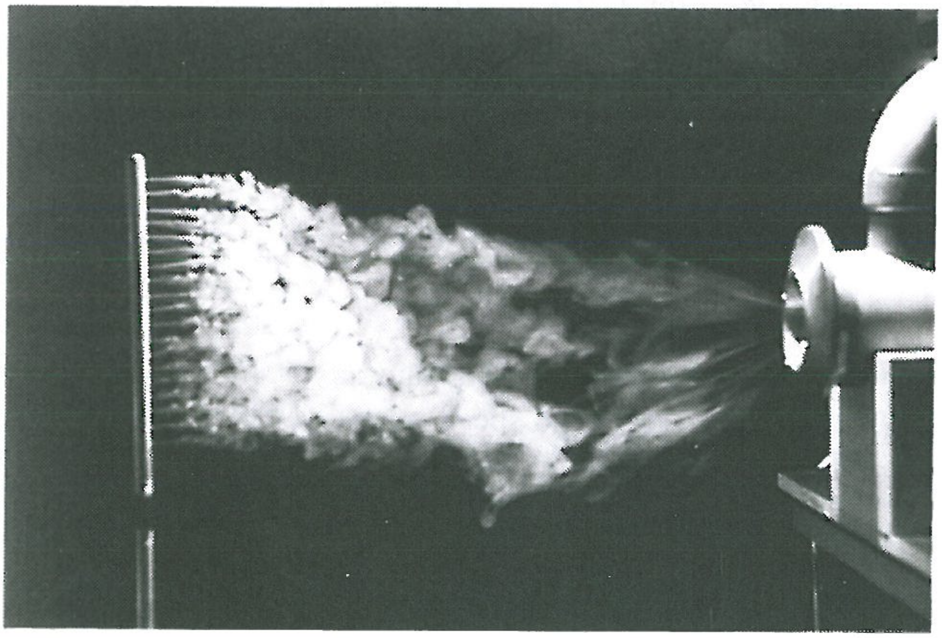

Figure 2.7 Exhaust with aerodynamic control of the air flow increases the exhaust efficiency considerably.

Instrumentation

In addition to the full-scale test rooms equipped with complete air-conditioning plants the Indoor Environmental Group has measuring equipment at a value of 3 to 4 million DKK at their disposal. The greatest importance has been attached to equipment for measuring indoor environmental parameters. The following list shows some of the most important equipment:

- Five data loggers which are mainly used for temperature measurements with thermocouples
- Two sets of equipment for measuring air velocities with 18 and 24 channels, respectively
- Two sets of gas analysis equipment for measuring CO_2 concentrations in a number of points
- One gas analysis equipment for measuring N_2O-, CO_2 and vapour concentrations in 6 points
- Twelve PC´s for data acquisition and data processing
- Two sets of advanced 1-channel velocity measuring equipment for wire probes or ball probes
- Nine pen recorders and multi point recorders
- Four sets of 1-channel air velocity meters
- Three smoke generators

Add to this equipment for measuring humidity, solid particle pollution, electrical quantities, wind direction and speed, pressure, flow in air and water, heat flow and heat radiation.

Normally, all measuring equipment is adjusted and calibrated at least once a year and in some cases just before it is used in a project. Calibration equipment is available for traceable calibration of the most important measuring equipment at the laboratory, however, this calibration equipment is not offered to external clients.

The measuring equipment is used both for student exercises, student projects and research at the laboratory and for field measurements in existing buildings.

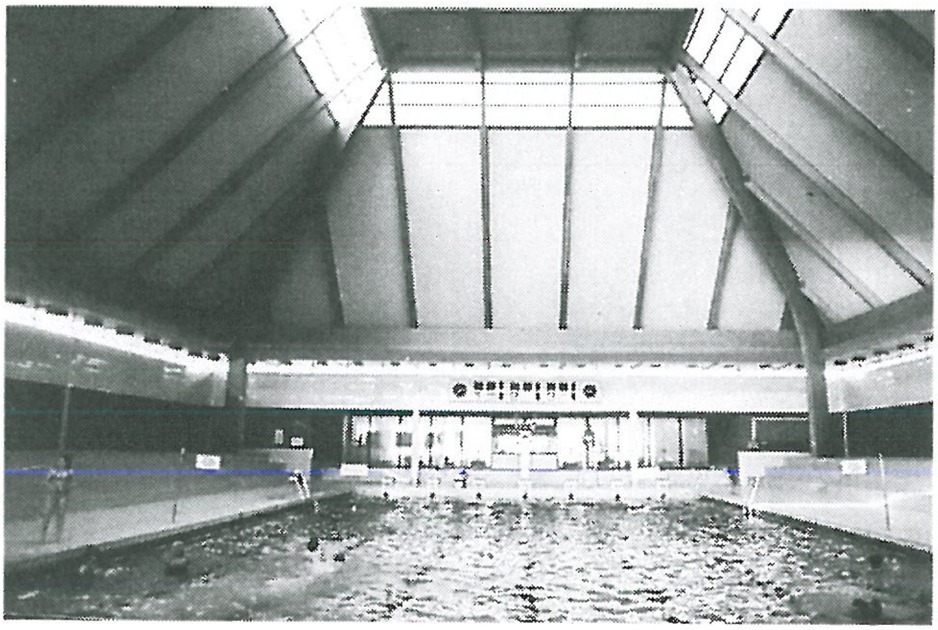

Figure 2.8 An example of full-scale measurements in a swimming bath. To avoid inconvenience for the users, it is attempted to make the measurement equipment as invisible as possible.

Thermal breathing manikin

In 1992 the Indoor Envir onmental Laboratory started using a thermal breathing manikin developed at the Danish Technical University. The manikin is shaped as a 1.7 m high average sized woman. The tight-fitting clothes have an insulation value of 0.8 clo. The manikin consists of a fibre armed polyester shell, wound with nickel wire used sequentially to measure the surface temperature and to heat the manikin to a specified skin temperature in 16 individual zones. The skin temperature and the heat output correspond to a person in thermal comfort. Measurements of personal exposure are performed with the manikin by means of an artificial lung, that can provide the respiration either through the mouth or through the nose. It is possible to control the respiration frequency (number of breaths per minute) and the pulmonary ventilation (litres per minute).

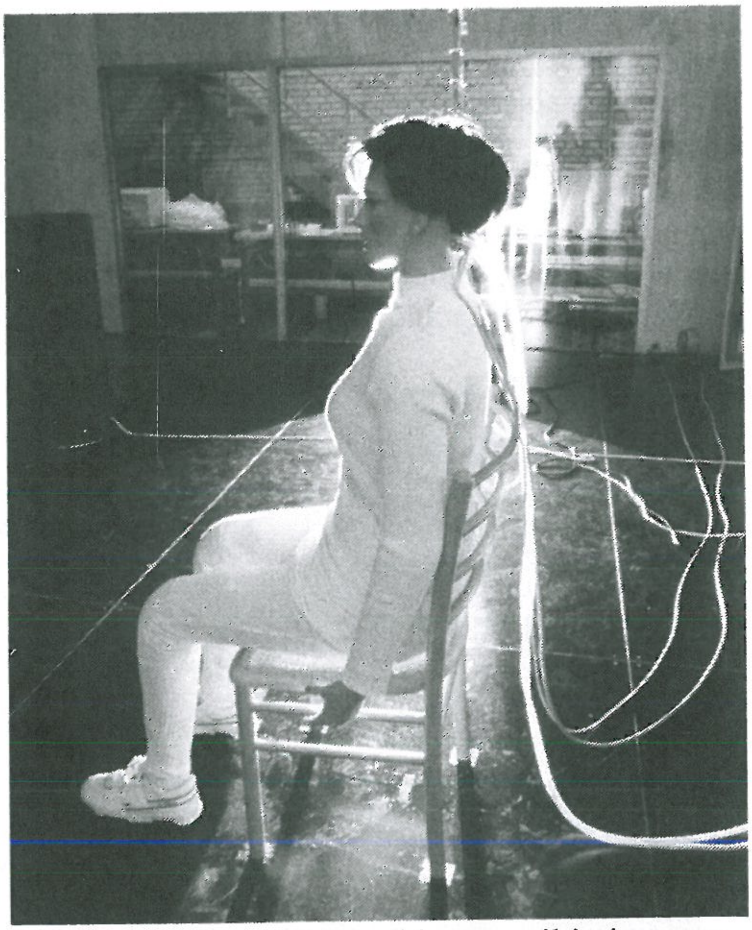

Figure 2.9 Thermal breathing manikin in operation.

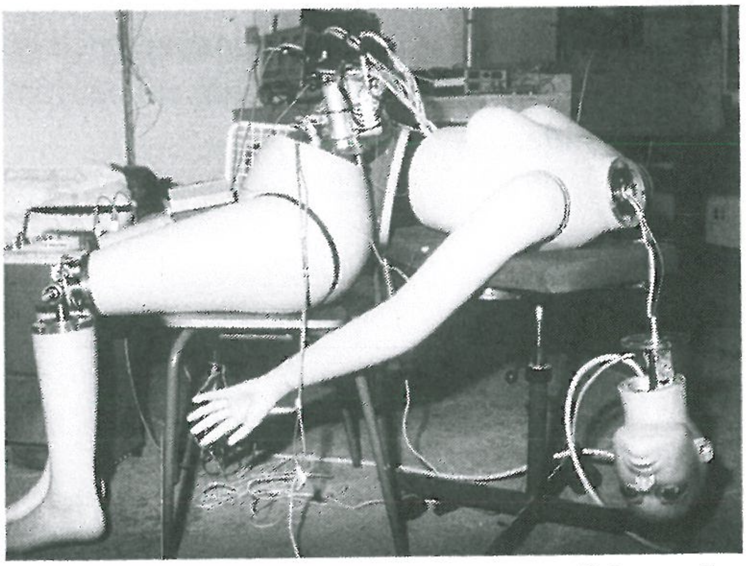

Figure 2.10 Thermal breathing manikin at the workshop.

2.4 Computers and software

Besides a number of personal computers, two workstations are at the disposal of the group for research purposes. Beyond this the group has access to a number of shared workstations at the department. The workstations are mainly used for CFD-calculations of air flow in ventilated rooms. During the evaluation period we have mainly used our own CFD-code based on the TEAM-code developed by the Department of Mechanical Engineering at UMIST (University of Manchester, Institute of Science and Technology, UK). For the simulation of thermal indoor climate, the group has PC-versions of the programmes SUNCODE, TSBI2 and TSBI3. Furthermore, the group has developed a number of PC-programmes for data acquisition and data presentation.

2.5 Education

The educational activities related to Indoor Environmental Technology are mainly part of the BSc curriculum (specialization in Building Technology) and part of the MSc curriculum (specialization in Indoor Environmental Engineering). Various courses are taught within the areas of indoor environmental technology, building services technology, air conditioning and ventilation techniques, district heating analysis, simulation and control of thermal systems and plants, computational fluid dynamics, air flow in rooms and measuring techniques. During the evaluation period the group has supervised 40 MSc Students and 21 BSc Students working with their thesis projects.

In 1994 an advanced PhD course in Numerical and Experimental Environmental Fluid Mechanics was arranged in cooperation with the Hydraulics Group at the Department of Civil Engineering, Aalborg University. The course had a duration of two weeks, and about 20 PhD students from five countries participated.

In 1993 and 1994 Mogens Steen-Thøde has served as chairman of the study board of the Building Technology curriculum and in 1993 he chaired the Self-Evaluation of the building technology and structural engineering programmes at Aalborg University (Steen-Thøde, 1993), which was prepared in connection with the project: Evaluation of civil and construction engineering programmes in Denmark. The project was initiated by the Technical Education Council.

Chapter 3
Research activities and results

In the long-term research plan from 1989, described in section 1.3, special effort was given to three research fields, namely Air Flow and Contaminant Distribution in Ventilated Rooms, Models and Control Strategies for Energy Consumption in Buildings and Influence of Outdoor Climate and Pollution on Indoor Climate in Buildings.

The first two fields were continued from the previous long-term research plan from 1986-1989. The results of these two fields are described in this chapter. The last research field was new and it was planned to start gradually in 1989 with increasing effort in the last part of the planning period. Due to the development in research resources during the planning period there has only been very limited activity in the area and, therefore, it has been omitted in this chapter.

3.1 Air flow and contaminant distribution in ventilated rooms

Purpose

The research within "Air Flow and Contaminant Distribution in Ventilated Rooms" comprises theoretical and experimental analysis of the flow processes created in rooms by the ventilation system, heat and contaminant sources, infiltration and exfiltration. The purpose of the research is to improve the understanding of flow processes in ventilated rooms and to develop calculation methods to predict the indoor environment in buildings. The research should result in new methods to optimize the use of air and energy in order to secure a comfortable and healthy working and living environment, taking into account the occupants' use of the building, the outdoor climate and the air distribution system.

Research activities

The research on Air Flow and Contaminant Distribution in Ventilated Rooms was originally based on field measurements and full scale laboratory measurements. Today, the research activities also include Scale Model Experiments and Computational Fluid Dynamics (CFD). The Indoor Environmental Group has applied all these methods during the evaluation period, and special attention has been paid to the combination of different methods in the research work.

The Indoor Environmental Group has participated in the international cooperative research activities within Annex 20 and Annex 26 sponsored by the International Energy Agency (IEA). In Annex 20 "Air Flow Pattern within Buildings" (1988-1991) research groups from about 10 countries joined a research cooperation that performed both full-scale experiments, scale model experiments and computational fluid dynamics, all used on a single geometry in a few different cases. This project gave a unique opportunity to compare and evaluate the results of different research methods and of different research groups and also to point out areas of possible and/or necessary improvements. In 1992 the Group joined Annex 26 "Energy-Efficient Ventilation of Large Enclosures" where the objective is to improve the understanding of air flow processes in large enclosures such as atria, auditoria, sports arenas, shopping malls, industrial halls etc. It is also the objective to develop analysis methods for designers to minimize energy consumption for ventilation of large enclosures. The Indoor Environmental Group serves as leader of the subtask on development of modelling techniques for air distribution in large enclosures. Participation in both projects has been supported by the Danish Energy Agency.

The group joined in 1993 the national research programme "Healthy Buildings" supported by the Danish Technical Research Council (STVF). The objective of the group's participation in this programme is to develop a mathematical model based on computational fluid dynamics to predict personal exposure.

The research activities concerning *Air flow and contaminant distribution in ventilated rooms* can be classified in eight principal subjects. Those subjects do not necessarily reflect the different research projects performed during the evaluation period because most projects performed include activities from more than one of the subjects. The research activities have been classified in the following subjects:

- **Mixing ventilation.** Design methods have been developed based on the combination of flow elements. Methods for the description of CFD boundary conditions are developed and contaminant distribution has been studied in full-scale experiments

- **Displacement ventilation.** The principle of displacement ventilation has grown popular within comfort ventilation during the last ten years. The buoyancy-driven flow from low momentum diffusers has been studied and described with semi-analytical models. Methods to handle boundary conditions and the effect of radiation have been developed for CFD

- **Industrial ventilation.** The research on this field has mainly been concentrated on exhaust principles. Capture efficiency has been studied for gaseous contaminants as well as for particles with and without an initial velocity

- **Agricultural ventilation.** Air quality in livestock buildings is a field of increasing importance. The effect of ceiling-mounted obstacles has been studied. Cold air jets have been studied in a full-scale room with symmetric and asymmetric heat distribution

- **Convection flow in room air.** Within this field basic experimental research has been performed on free turbulent plumes from different heated bodies and on free turbulent boundary layer flows from plane walls and walls with large obstacles

- **Efficient ventilation of large enclosures.** Different research methods such as Flow Element Models, Scale Model Experiments and Computational Fluid Dynamics are compared considering the prediction of air flow and temperature conditions in large enclosures

- **Contaminant transport in the indoor environment.** This field includes the investigation of indoor air pollution and transport processes for the contaminants. The local air flow around a person and the personal exposure have been investigated to develop models for predicting the indoor air quality which is actually experienced by a person in a ventilated room

- **Numerical simulation of air distribution in rooms.** The work is concentrated on the application of CFD-codes to calculate room air flow. The major effort is concentrated on the specification of suitable boundary conditions for the items affecting the air flow

On the following pages, the subjects listed above are described in further details.

Mixing ventilation

One of the main purposes of a ventilation system is to ensure uniform and acceptable conditions in the occupied zone. In a ventilation system of the mixing type the fresh air is led into the enclosure by one or several jets located outside the occupied zone. These jets have a significant impact on the flow field in the entire room and, consequently, also in the occupied zone. The jets are created by inlet diffusers which often have a very complex geometry. The research into mixing ventilation is traditionally based on full-scale experiments and especially on experiments which are concentrated on the jet flow from the diffusers. The jet flow from five different diffusers - and the corresponding room air motion - were measured by full-scale tests, Heiselberg (1990). It was stated that the air change rate in a room with mixing ventilation has to be relatively high to have fully developed turbulence.

The participation in the International Energy Agency (IEA) research work "Air Flow Pattern within Buildings" included full-scale experiments with mixing ventilation, Skovgaard, Hyldgård and Nielsen (1990).

The design of an air distribution system can be based on full-size investigations, scale model experiments or CFD simulations, but the most convenient method in many practical situations is to design the system from the flow element theory. The flow elements are isolated volumes where the air movement is controlled by a restricted number of parameters and the air movement is fairly independent of the general flow in the room. A free jet from a supply opening is a typical example, because the flow is governed by the supply momentum flow and it can typically be described by parabolic equations. Heiselberg (1994) has worked with the combination of a free jet and different geometries and locations of a heat source to develop a flow element design tool for this situation. Nielsen (1991, 1994d) has given design methods based on the following flow element combinations: Throw of isothermal jet, Deflection of a jet at the end wall, Penetration length of non-isothermal wall jet.

The basic idea of mixing ventilation is to create a recirculating flow which will absorb the contaminant from different sources in such a way that the local concentration is low everywhere in the room. The name: "Mixing ventilation" implies that the concentration is mixed to the same level everywhere in the room but, on the other hand, the transport of contaminants must involve a turbulent diffusion term as well as a convection term which will result in concentration gradients. The concentration can therefore be high in certain areas which is shown by Heiselberg (1990,1991). Furthermore, a ventilation effectiveness much smaller than 1.0 can be obtained as documented by Heiselberg (1990) and Nielsen (1992a).

One PhD thesis (Heiselberg, 1990) was published during the evaluation period.

Displacement ventilation

For many years buoyancy driven displacement ventilation has been used in industrial areas with high thermal load as, e.g. in buildings with heat emitting processes as in the steel industry. The displacement ventilation system has also grown popular during the last ten years as comfort ventilation in rooms with low thermal loads as, e.g. in offices. Some main features of displacement ventilation are the possibilities of creating both high temperature effectiveness and high ventilation effectiveness. The supply openings are located at a low level in the case of displacement ventilation and the air flows directly into the occupied zone. Free convection from heat sources creates a vertical air movement in the room and the heated air is removed by return openings located in the ceiling or just below the ceiling. It is thus the free convection or the buoyancy which controls the flow in the room, while the momentum flux from the diffusers is low and without any practical importance to the general flow in the room.

The flow from heat sources and cold surfaces is reported in the chapter "Convection Flow in Room Air" and the research on contaminant distribution in the room is reported in the chapter "Contaminant Transport in the Indoor Environment". Therefore, this chapter will address the work made in the Indoor Environmental Group on stratified flow in a room with displacement ventilation and the work made on models for the vertical temperature distribution.

The air is supplied into the occupied zone from a low velocity wall-mounted diffuser. The achievement of a quantitative description of the flow along the floor is important because this buoyancy driven flow is the only air movement which influences the occupants' comfort. A description of this air movement - and the vertical temperature gradient - will therefore make it possible to obtain a detailed picture of the thermal comfort in the room.

The first part of the work was reported by Nielsen (1990a), and it shows the characteristic velocity decay for the stratified flow in the room. The results were later extended by Nielsen (1992c) and Jacobsen and Nielsen (1992). Their measurements on seven different diffusers show that the velocity level in the floor region was individual for the diffusers and formulas were given for the velocity decay. Nielsen (1994b, 1994f) describes a semi-analytical expression which can be used to predict the flow from a given diffuser and the velocity decay at floor level in a large part of the room. The differences between a radial stratified flow and a two-dimensional stratified flow obtained, e.g. in a long and narrow room is addressed by Nielsen (1994a).

A displacement ventilation system exploits efficiently the use of energy because it is possible to remove exhaust air from a room with a temperature that is several degrees above the temperature in the occupied zone. This process will allow a higher air inlet temperature at the same load in comparison with mixing ventilation. It is necessary to have a design method for the temperature distribution used for instance in connection with the flow element method and the energy calculations. The temperature distribution is also important in connection with thermal comfort in a room. It is necessary to consider the temperature gradient in the occupied zone, as well as the asymmetric radiation from the ceiling, in connection with the design of a displacement ventilation system and the evaluation of thermal comfort.

Nielsen (1992a) shows that the different vertical temperature gradients are obtained from different heat sources and that a typical gradient is preserved in cases where people move around in the room and doors are open for short periods. A model for the vertical temperature gradient is given by Nielsen (1995e). This model gives the gradient as a function of the Archimedes number of the flow and as a function of the four different heat sources: Extensive heat sources, sedentary persons, ceiling light and a point heat source.

The model is further extended with the possibility of expressing a non-linear temperature gradient either in the case of plume stratification at a certain height or in the case of different vertical positions of the heat source.

One PhD thesis on displacement ventilation, Jacobsen (1993), and one book on the subject, Nielsen (1993c) have been written during the evaluation period.

Industrial ventilation

There is an increasing awareness of the importance of a well-designed air distribution system in the industrial environment. Threshold values for contaminants are reduced through the years and new contaminants are introduced into the indoor environment. This tendency will increase the importance of design methods for air distribution systems and local ventilation. Furthermore, there is a general pressure to reduce the very large energy consumption within the industrial ventilation in Denmark.

This development is the background for the research group' s work on optimization of local ventilation as for example capture hoods, receiving hoods and different designs of the enclosuring principle as well as research on the exposure of people.

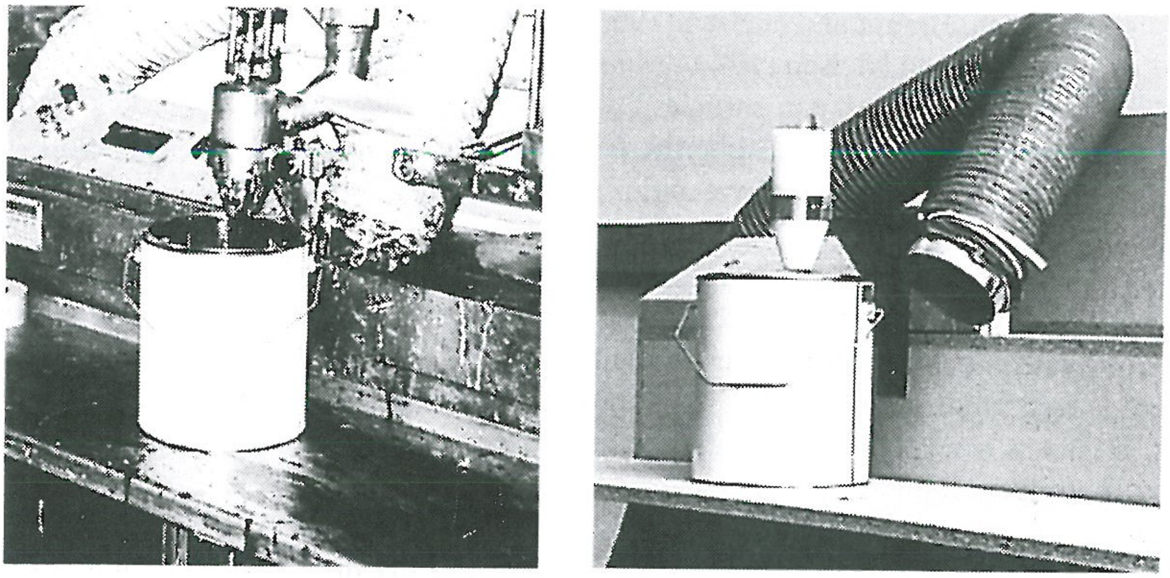

Figure 3.1 Machine for filling of cans and identical full-scale model for laboratory experiments. Nielsen, Madsen and Tveit (1991).

Figure 3.1 indicates the methods which are used in the research on local ventilation. Initial measurements at the working place are made for identification of the problems. The next step is to make measurements on a scale model of the equipment using tracer gas with a high concentration level, and the last step is to improve the local ventilation with, e.g., enclosuring or changing of the working routine in connection with the process. Modifications on the paint filling machine in figure 3.1 allowed a 65% reduction of the exhaust flow rate and an improved overall performance of the local ventilation.

For some years, up to the evaluation period, the Indoor Environmental Group has been engaged in research work on a special exhaust system reinforced by jet flow (figure 2.7). Continuous work on this system in cooperation with the Danish Technological Institute and the company Nordfab A/S gave a description of the quantitative performance of the system, and it was shown that a high capture efficiency could be obtained at a large distance from the exhaust opening without any application of enclosuring, Pedersen and Nielsen (1991) and Germann (1991).

Capture efficiency is an important design parameter for local ventilation. Work has been carried out in cooperation with the Danish National Institute of Occupational Health and Institut National de Recherche et de Sécurité in France to study practical methods for the determination of the capture efficiency for different equipment. Most of the work is carried out on a capture hood. Methods are indicated for both experimental approaches and for Computational Fluid Dynamics approaches, Madsen, Breum and Nielsen (1993a, 1993b, 1994), and Madsen, Aubertin, Breum, Fontaine and Nielsen (1994). Many contaminant sources in industrial areas have an initial velocity as, e.g. particles from a grinding wheel, and this has been addressed by Madsen, Fontaine, Aubertin, Nielsen and Breum (1995) for many combinations of particle sizes, initial velocities and draught in the surroundings.

The thermal manikin is a very efficient tool for personal exposure measurements. For example it has been shown that there may be a large variation in concentration within the breathing zone defined for location of exposure measuring equipment and, furthermore, it has been shown that the exposure from a local source (typical for a working situation) can be 50 times as high as the level calculated from the fully mixed theory, Brohus and Nielsen (1995a).

Industrial ventilation has been addressed in PhD theses by Germann (1991) and Madsen (1994), and in a congress opening lecture by Nielsen (1994e).

Agricultural ventilation

During the last decades livestock production has developed rapidly towards larger and more intensive production systems. In modern production systems air quality is important to animal welfare and important to the health of people who are full-time employed in animal production. Under these conditions the design of proper ventilation systems has become a subject of increasing importance.

Traditional methods for the prescription of air distribution in farm buildings are mainly based on experience and simple Flow Element Models. When these methods are used it is not possible to include the effects of room geometry and obstacles. Furthermore, traditional methods provide no possibilities to calculate important parameters such as contaminant concentration and ventilation efficiency for the ventilation system.

The use of Computational Fluid Dynamics (CFD) to simulate air distribution and contaminant distribution in agricultural buildings has been studied in cooperation with the Royal Veterinary and Agricultural University in Copenhagen, Denmark. It has been shown that CFD is a useful tool to predict air velocities in cases where the air flow is affected by obstacles (Christensen 1992) or by other structural details. The problem of specifying boundary conditions for air inlet devices with a complex geometry was studied (Svidt 1994a), as well as the calculation of non-isothermal flow (Svidt 1993). A larger report on the subject was written in Danish for the use of the farmers' extension service (Svidt 1994b).

Convection flow in room air

Convection flow in room air has been an important research topic for two reasons. The first reason is the fact that during the eighties vertical displacement flow grew popular as comfort ventilation. In displacement ventilation the efficiency of the ventilation system depends on the relationship between the ventilating air flow rate and the air flow rate in the convection flow, which means that the estimation of this flow becomes very important. The second reason is that in large enclosures, where the room height is significant, the energy and air distribution within the space will often be determined by the convective flow, rather than by the ventilation system.

A comprehensive basic research work has been performed on free turbulent plumes from different heated bodies (Kofoed 1991). Three different measurement methods were developed to analyse the volume flow in plumes, where the extrapolation method proved to be superior and resulted in valuable new experimental knowledge (Kofoed and Nielsen 1990). The theory of a pure plume above a point heat source was verified, and it was shown that the plume axis wandering has to be treated as a phenomenon of large-scale instability and not as a turbulence phenomenon. The influence of even very small vertical temperature gradients (0.1 °C/m) was reported to be significant, and a considerable reduction of the vertical volume flow was found when the buoyant flow took place near to enclosing walls, i.e. the volume flow rate in a wall plume is only 63% of the volume flow in a free plume

(Kofoed and Nielsen 1991b). The experimental results have formed the basis of both analytical and numerical research work on plumes of several international researchers.

Another type of convection flow is the free or natural convection flow along vertical surfaces. This flow has also a great influence on the vertical temperature and contaminant distribution in displacement ventilated rooms as shown by Heiselberg and Sandberg 1989, and along cold surfaces they are often the cause of draught in the occupied zone. Measurements in the free convective turbulent boundary layer flow (Heiselberg 1990, Heiselberg and Sandberg 1990) showed much lower velocities and larger boundary layer thicknesses than the ones predicted by the relations traditionally used in engineering applications. In spite of this, the predictions of the volume flow, which is the most important parameter in designing displacement ventilation systems, were acceptable. In relation to thermal discomfort the important issue is, however, not the maximum velocity close to the surface, but the maximum velocity in the occupied zone after the boundary layer flow has reached the floor and changed direction. Models for the development of velocities and temperatures in the stratified flow along the floor in the occupied zone have been established (Heiselberg 1993b, 1994f and 1994b) through measurements in the laboratory. These models have created the basis for predictions of the percentage of dissatisfied persons (PD) due to cold downdraught. The predictions have shown that at window surfaces of normal room height or less, downdraught can be avoided passively by using windows with good insulation properties (Heiselberg 1994d and 1994e). Higher surfaces will always cause problems and, consequently, some kind of active measure will be necessary. Common to all the active measures that are used today is the fact that they increase the energy consumption. Therefore, it has been investigated if the structural system of glazed facades can be used to reduce downdraught and to avoid thermal comfort problems in the occupied zone (Heiselberg, Overby and Bjørn 1994 and 1995). Two PhD-theses by Heiselberg 1990 and by Kofoed 1991 were published during the evaluation period.

Efficient ventilation of large enclosures

Large enclosures, for example concert halls, sports arenas and ice rinks, office buildings, factory spaces, atria, shopping centres or passenger terminal buildings often present unsolved problems related to energy and air flow such as unwanted thermal stratification, local superheating, draught or uncontrolled contaminant spreading. In large enclosures common ventilation strategies like complete mixing, require a large amount of energy to move and to condition an enormous amount of air. The air flow pattern should therefore be well planned and controlled to ensure an acceptable indoor air quality in the occupied zone without the need for excessive air flow rates. This is obviously possible because in large enclosures the occupied zone is relatively small.

Some of the initial work performed on efficient ventilation of large enclosures was on ventilation and air conditioning of public swimming baths. Full-scale and field experiments of the evaporation in swimming baths by Hyldgård 1990 gave rather revolutionary results that caused radical changes in carrying out and running of swimming baths. The changes resulted in both reduced investments, reduced working expenses and in addition a better comfort for the bathers.

The participation in IEA-ECB Annex 26: "Energy Efficient Ventilation of Large Enclosures" from the middle of 1992 has given an increase in the effort within this field. The objective of Annex 26 is to increase the understanding of the physics of air motion, thermal stratification and contaminant distribution in large enclosures and to develop methods to minimize energy consumption in consideration of good indoor air quality and thermal comfort. In the research work different methods such as Flow Element Models, Scale Model Experiments and Computational Fluid Dynamics (CFD) have been used to predict air flow and temperature conditions in large enclosures. The capabilities of the different methods have been evaluated through comparisons between full-scale and model scale experiments in the laboratory, and through predictions and investigations within this field.

The work by Nielsen 1993a, Fox and Nielsen 1993 and Nielsen 1995a on the Danish Pavilion at the 1992 World Exhibition in Seville showed that both Scale Model Experiments and CFD were efficient tools to predict the air flow distribution. Tha work showed that even a very simplified configuration of CFD predictions could give valuable information for further design work. The Flow Element Models method is very useful in situations where the air flow pattern in a room is dominated by a single flow element. However, in large enclosures different flow elements will occur simultaneously, and the air flow pattern will depend on the individual strength of each element and on the way they act together. Heiselberg 1994c showed that it was possible to estimate the thermal comfort from the traditional air jet theory (Flow Element Models) in a large enclosure with both ventilating jets and powerful heat sources. For an estimation of the indoor air quality and the ventilation effectiveness it was, however, necessary to know the influence of the heat sources on the air flow pattern.

Contaminant transport in the indoor environment

One of the main purposes of the air distribution system in the indoor environment is to remove the contaminants from the occupied zone as quickly and efficiently as possible, and to supply the occupants with fresh air. The first research work concentrated on characterizing the two main air distribution principles, mixing ventilation and displacement ventilation (Heiselberg 1990, Nielsen 1992a) by their ventilation effectiveness and air exchange efficiency.

Although the basic idea behind mixing ventilation is to obtain a complete mixing of the air, the research showed that gradients in the contaminant distribution would often occur, and that the contaminant distribution was a function of the air change rate, the location of the return opening, the location of the contaminant source and the density of the contaminant (Heiselberg 1991a, 1992a and 1993a). Natural convection flow from heat sources seemed to increase the mixing process.

The idea behind displacement ventilation is to displace the contaminated air from the occupied zone and to achieve supply air quality here and exhaust air quality in the rest of the room and thereby ensure a high ventilation effectiveness. This is obtained in many practical situations, especially if the contaminant source is also a concentrated heat source. This is even the case in a room with both stationary and movable sources (Nielsen 1992a). However, if the contaminant source is isothermal, or at the same time a distributed and weak heat source, this may cause high local concentration levels (Heiselberg and Sandberg 1990, Nielsen 1992a).

In 1993 a five-year research programme "Healthy Buildings" was initiated in a cooperation between the Technical University of Denmark, Danish Building Research Institute, University of Aarhus, Danish National Institute of Occupational Health and the Indoor Environmental Group at Aalborg University. The research programme is sponsored by the Danish Technical Research Council (STVF). The research programme has its background in problems related to the indoor environment. The aim is to improve the understanding of the indoor air contaminant sources, the transport of the contaminant in the ventilated environment from the sources to the occupants, and finally to examine the personal exposure (Nielsen et al. 1995, Nielsen 1995d).

The research programme is divided into three parts: Indoor air pollution sources, Transport processes and Effects of indoor air quality on occupants. The Indoor

Environmental Group is responsible for the part "Transport processes" which subsequently will be further discussed.

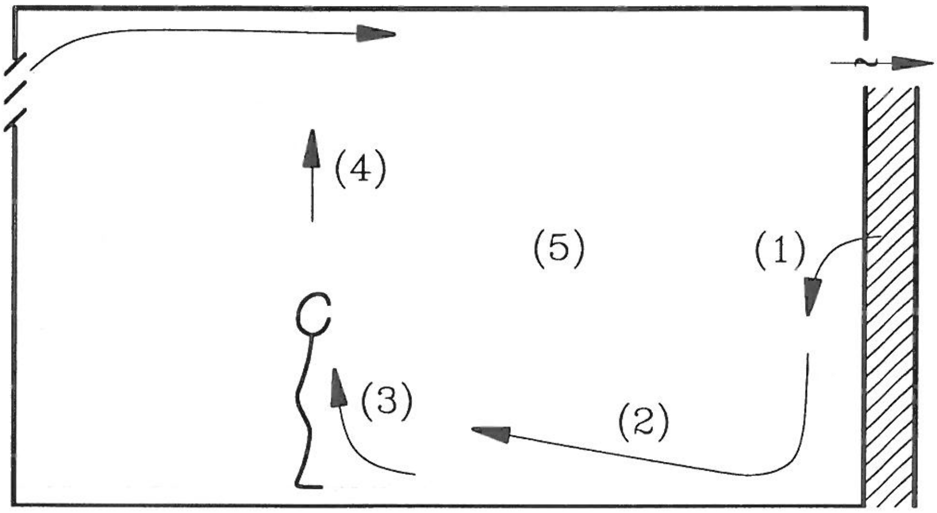

Figure 3.2 Transport processes in the indoor environment.

Figure 3.2 shows the elements of a transport process. A contaminant is emitted from a pollution source, e.g. a surface material (1), and transported by convection and diffusion through the room (2). The convective ascending air currents around a person entrain and transport the contaminant giving rise to personal exposure (3). The person acts as a heat source and a contaminant source at the same time (4).

The emission of contaminants from surfaces (1) has been examined by means of CFD (Jensen and Nielsen, 1995). A Low Reynolds Number model has been applied in the numerical solution scheme to simulate the behaviour of the emission process in close proximity to a surface. A method for the translation of results from small-scale experiments into full-scale has been developed. Employing this method it is possible to use low-cost experiments to investigate the impact of different materials on the indoor air quality (Jensen and Nielsen 1995).

The local air flow around a person and the personal exposure (3) have been investigated to develop models for predicting the indoor air quality which is actually experienced by a person in a ventilated room. Measurements were performed by means of the breathing thermal manikin (figure 2.9). Measurements were performed with the manikin placed in a displacement ventilated room and in a wind channel with a well defined air flow. When concentration gradients prevail in a room the presence of people will modify the indoor air quality locally and affect the personal exposure. Several parameters exert an influence in the interaction between persons and the ventilation, e.g. the thermal boundary layer around persons and the local disturbance of the air flow. Both parameters are found to be very important (Brohus and Nielsen 1994b).

In the case of a uniform flow field, velocities ranging from approximately 0.1 m/s are found to influence the contaminant transport in the vicinity of persons considerably (Brohus and Nielsen 1994b, Hyldgård 1994a). The wind channel measurements have been compared with calculations where the enclosure is assumed to be well-mixed. The comparison shows personal exposure deviations of an order of magnitude (Brohus and Nielsen 1994b, 1995a). A model for predicting the personal exposure in displacement ventilated rooms has been developed. The model takes the entrainment in the human boundary layer as well as the concentration stratification into account (Brohus and Nielsen 1995b).

A person influences the surrounding air by emission of heat and contaminant (4), for instance due to bioeffluents and smoking. The impact of heat emission from a person has been studied by means of velocity measurements in the plume above the thermal manikin. Tracer gas measurements have shown that bioeffluents and water vapour generated by perspiration follow the convective ascending current along the body and continue to rise above the head - unless the person is exposed to a horizontal velocity field of a certain level (Hyldgård 1994a). Measurements on the respiration reveal that the inhaled air comes from the convection current in front of the chest (Brohus and Nielsen 1994b, Hyldgård 1994a). By tracing the expired and contaminated air, it appears that no short circuit between the inhaled and expired air takes place under normal circumstances (Hyldgård 1994a).

To calculate the convection and diffusion in a ventilated room (2) a CFD-model is under development. This programme solves the general flow equations numerically using a standard two-equation turbulence model and the SIMPLE algorithm (Nielsen 1994e, 1993b). To simulate the indoor air quality an equation for transport of contaminants has been implemented in the CFD-programme. This concentration equation accounts for the transport of non-buoyant gasses, small particles and perceived air quality (Nielsen et al. 1995). The final CFD-model will be able to predict the indoor air quality including the elements (1) - (4). This is done by implementing boundary conditions as subroutines containing the developed models.

Numerical simulation of air distribution in rooms

The fluid dynamics research is strongly influenced by the increasing computer power which has been available for the last decades. This development has the effect that the cost for a given job will decrease by a factor of 10 during every eighth year. The development shows not only a decreasing cost but the computer time is also decreasing. There are several reasons for this development. Firstly, the computer efficiency is increasing more rapidly than the computer costs and this tendency seems to continue. Secondly, a process takes place which increases the flexibility of different software as pre- and post-processor software and, furthermore, there is a continuous development of new software.

These tendencies have also influenced the indoor environmental technology. One of the first examples of a prediction based on Computational Fluid Dynamics (CFD) in indoor environmental technology was internationally published by a member of the research group in 1973. The activities have increased dramatically since then and especially during the last years. It can be mentioned that all CFD papers at the first ROOMVENT conference in Stockholm in 1987 were presented within a single session, while half of all papers at the third ROOMVENT conference in Aalborg in 1992 were based on, or included, CFD calculations.

Codes developed at different universities and commercially developed codes are today available for the general prediction of air distribution in rooms. It is therefore necessary to direct the activities to restricted research areas to be able to be leading within new development. We have decided to ignore the general software development as for example new numerical methods, new turbulence models, etc., and instead we are working directly with improvements of software in connection with indoor environmental problems. The activities can be summarized in the following points:

- examine if the physical processes in ventilation can be predicted by CFD and, furthermore, identify areas with problems and types of problems
- develop software which is necessary for an efficient application of CFD in indoor environmental technology
- examine if new software made for other fluid dynamics problems can give an improved solution of the physical processes in ventilation
- make measurements for the validation of the different CFD methods

At the beginning of the evaluation period the research activities were mainly connected to the activities sponsored by the International Energy Agency (IEA). This was during the period 1988 - 1991 and the subject was "Air Flow Patterns within Buildings". The CFD work was divided into a two-dimensional case and a three-dimensional test case. The two-dimensional test case was specified by our research group, Nielsen (1990c), and the corresponding isothermal predictions agreed very well with measurements made by Skovgaard and Nielsen (1991B, 1991D).

The three-dimensional predictions gave a large variation in the results from the different countries. The description of boundary conditions at the diffuser was one of the important problems, and our work was concentrated on the development of improved descriptions of this component. Figure 3.3 shows the results for a Simplified Boundary Condition which is the description normally used by CFD predictions. Comparison with measurements shows that the maximum velocity in the occupied zone is overestimated by 40%.

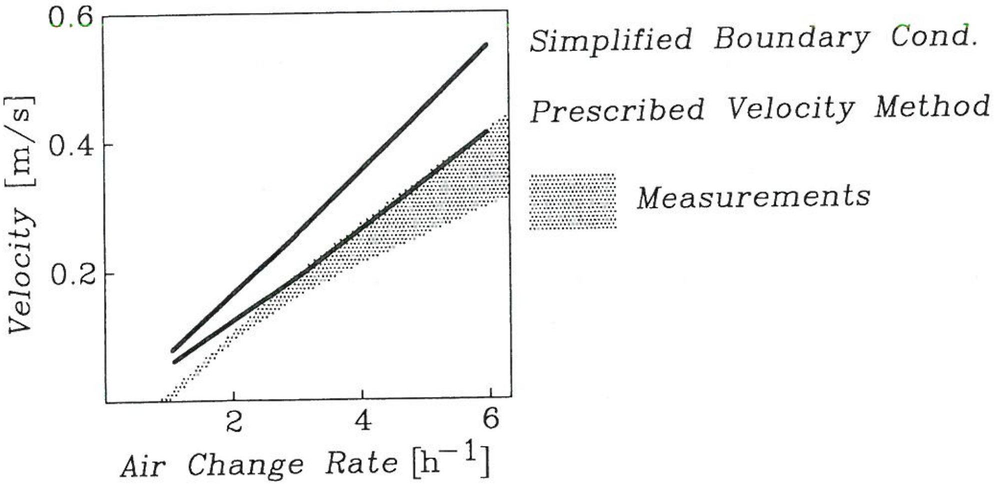

Figure 3.3 Maximum velocity in the occupied zone of a room with mixing ventilation.

Figure 3.3 shows the improvement of the predictions obtained by the use of a prescribed velocity method given by Nielsen (1989a, 1992b and 1994c), Skovgaard and Nielsen (1991c) and Skovgaard (1991).

Another subject within the IEA programme was work on improvements of turbulence models. A low Reynolds number model proved to be suitable for recirculating flow, but the model was not able to predict penetration length in deep rooms, Skovgaard and Nielsen (1991d) and Skovgaard (1991).

Some work has been made on displacement ventilation. Two factors are important. A large part of the energy transport takes place as radiation and the flow vary from areas with a high turbulent level to areas with almost stagnant air. Those problems have been studied by Jacobsen (1993) and Jacobsen and Nielsen (1993). Models for radiation between surfaces and damping functions which take account of laminar flow and stratification effect have been tested and compared with measurements.

Computational Fluid Dynamics has also been used within other fields such as ventilation of livestock buildings and industrial buildings. Svidt (1992, 1993 and 1994) has worked with obstacles below the ceiling, cold supply jets and a prescribed velocity method for livestock buildings, and Brohus (1992) has worked with obstacles in the occupied zone of a building.

Capture efficiency of local exhaust openings is one of the important details of air distribution in industrial buildings. The conventional CFD method is based on a Eulerian description which is not comprehensive enough for the prediction of capture efficiency. Madsen (1994) has extended the model with a Lagrangian approach for a gas and particle movement. The results are given by Madsen et al. (1994, 1995).

The work on the Healthy Building Programme also involves CFD methods. Low Reynolds number models have been used both for work on scaling problems in connection with small-scale test chambers, Jensen and Nielsen (1995), and also for the prediction of the concentration distribution around a person, Brohus and Nielsen (1995).

Work on CFD has been reported in the following theses and large reports by Skovgaard (1991), Jacobsen (1993), Madsen (1994) and Svidt (1994b) and in conference opening lectures by Nielsen (1992a, 1994d and 1994e).

3.2 Models and control strategies for energy consumption in buildings

During recent years energy conservation and energy management have become increasingly important concepts. People involved in the design and management of buildings are aware of the need for design tools which allow an accurate prediction of energy consumption and performance characteristics at an early design stage. The design tools could also be used to appraise operational options throughout the life of the building to maintain an optimum energy consumption. Building energy analysis systems can be used to provide insight into comfort, energy saving and management strategies, the optimum configuration of the building components, and the impact of various operational regimes.

Dynamic modelling of energy flow in buildings and the associated climatic control systems is complicated. The modelling of the thermal performance of a building requires a detailed knowledge of a number of subsystems: The building form and structure; The layout and operational characteristics of the plant and the control system; Air infiltration and movement; The actions of the users of the building.

Despite the relative importance of this research area the activity has been modest during the period but three projects are in progress:

- Dynamic room models
- Vertical temperature gradients in rooms with convective flow
- Design and control of HVAC system components

Dynamic room models

In this project different numerical models for thermal analysis of building components have been studied and computer programmes have been developed. The programmes are prototypes meant for analysing and calibrating purposes and they are a valuable tool for the study og complex thermal phenomena in buildings.

A three-dimensional dynamic model (Evensen 1990, 1992) and a simple two-dimensional steady state model (Steen-Thøde 1992) have been programmed and used to study the influence of multidirectional heat flow in building components. Several comparisons between room temperature simulation results and measurements in a laboratory test room have shown that multidirectional heat flow (from thermal bridges etc.) contributes significantly to the difference between experimental and calculated results based on one-dimensional models. Consequently, there is a need to establish procedures to adjust the input data to room temperature simulation programmes based on one-dimensional heat conduction models in order to counteract this effect.

A program package for analysis of dynamic temperature and heat flow in one-dimensional multilayer walls has been developed (Steen-Thøde 1989, 1994). The governing partial differential heat equation has been programmed in both a control volume and a finite element method and given a state-space formulation. The state-space representation gives a very flexible package which can be used to calculate both time-domain and frequency-domain response. Furthermore, the frequency response can be compared with the "exact" frequency response calculated from the overall wall transmission matrix. The program package can be utilized as the basis of parametric studies to examine alternative numerical methods and spatial discretization schemes. The intention is to extend the program with a room model with the same facilities as mentioned above which can serve as a reference model in thermal control analysis and studies of building operation dynamics.

Vertical temperature gradients in rooms with convective flow

A review of programmes for simulation of temperature conditions in buildings shows that the programmes normally do not consider the thermal inhomogeneity of room air. Therefore, no information is given of the temperature distribution in the air. In addition to that, the long wave radiation between surfaces of different temperatures is often distributed via the air node, which means that the calculated air node temperature will be a weighted air and surface temperature.

This project (Overby 1990) deals with measuring and calculation of vertical temperature gradients in radiator heated rooms. Through laboratory experiments a simple model, which predicts the vertical temperature gradient, has been developed. The gradient is calculated from a dimensionless temperature profile which is determined by two room air temperatures only: the mean temperature in the occupied zone and the mean temperature in the zone above the occupied zone. Actually, there are two dimensionless gradients, one for heating periods and one for cooling periods, due to the fact that the air temperatures close to the floor and the ceiling are strongly influenced by the surface temperatures.

A two-zone room model for calculation of the air temperature in an upper and in a lower room zone has been developed. The energy transport between the two air nodes is described from the flow paths of the free convection in the room and the radiant interchange between the surfaces. The model is implemented in Suncode-PC, a commercial thermal analysis programme.

The modified programme is able to calculate the temperature gradient in the room based on two simulated air temperatures and on the dimensionless temperature profile for heating and cooling periods. The validation of the programme against measured temperatures in the laboratory test room shows that the calculated surface and air temperatures are closely following the real conditions, and a good estimate of the vertical temperature gradient in the test room is obtained (Overby 1993, 1994).

Design and control of HVAC system components

Heating and cooling coils in air-conditioning systems are frequently misdesigned which may cause control difficulties. Hence investigations of the influence of different design parameters and dynamic modelling of HVAC equipment is important.

Steady state performance characteristics of a cooling coil with a water-glycol mixture refrigerant have been measured, and the decrease in cooling output relative to the output with pure water as refrigerant has been calculated (Hyldgård 1993). These results show that the cooling output will be overestimated if the influence of the thermophysical properties of the anti-freezing additive is disregarded.

For the purpose of control system design studies a model for dynamic simulation of heating coils with constant fluid flow has been programmed, taking into account time delays and non-linearities in the control loop (Steen-Thøde 1994).

3.3 Status and Discussion

The year 1986 was a turning point for the research activities within Indoor Environmental Technology when Peter V. Nielsen was appointed professor in Indoor Environmental Technology. The first long-term research plan for the Indoor Environmental Group was initiated and the research activities have been developing since then, especially during the last three years of the evaluation period.

Research activities and results

Research activities within the field of **mixing ventilation** were especially high in the beginning of the evaluation period. A number of supply openings were tested and adapted to flow element models. It was shown that concentration gradients always are present in the room, although the name "mixing ventilation" indicates that the flow should be fully mixed. Furthermore, it was shown that there is a low turbulent effect in the flow at small velocities, which can be a problem in connection with the use of computational fluid dynamics at low velocities.

Research activities within the field of **displacement ventilation** have taken place during the whole evaluation period. Most of the work has been directed towards the stratified flow from wall-mounted diffusers, and semi-analytical expressions have been developed from the velocity distribution at floor level. The work can be used in design procedures as well as being a tool in product development in connection with new supply openings. New heat source dependent expressions for vertical temperature gradients have also been developed and adapted to flow element models for an easy-to-use design procedure.

Industrial ventilation is another important research field. Work on selected local exhaust systems has shown that it is possible to make considerable savings on energy consumption combined with an improved air quality. The research is done in an efficient way by full-scale models of equipment and by use of tracer gas. The group has also made a more fundamental research on the capture efficiency concept, and a practical method is indicated for a correct estimate of the capture efficiency for capture hoods.

Research on **Ventilation in livestock buildings** is often a special application of mixing ventilation. The heat load in livestock buildings is very high and the investment in the ventilation system has to be very low which makes heavy demands on the design of the system. A member of the group has worked on this area using computational fluid dynamics and full-scale experiments. A great step forward has been made in the specification of boundary conditions, such as supply openings, obstacles and heat load distribution.

Convective flow in rooms is an important research topic, both in connection with design of displacement ventilation and ventilation of large enclosures. A comprehensive basic research work has been performed on free convection from heat sources, and the results have formed the basis of both analytical and numerical research work on plumes of several researchers. Work on downdraught has given design procedures both for windows of conventional sizes and for windows and surfaces in large enclosures as, for example, atria.

A large part of the activities within the field of **Efficient ventilation of large enclosures** has been made in cooperation with a number of IEA countries. This work has been important for the foundation of our international connections within air distribution in room, and one of our group members is subtask leader in this international project. The project work involves computational fluid dynamics and scale-model experiments. Efficient ventilation of large enclosures is the only research area which has involved scale model experiments.

Contaminant transport in the indoor environment is one of the most important research fields of the Indoor Environmental Group. This subject has been treated during the whole evaluation period, and most of the research is based on full-scale measurements on tracer gas distribution and computational fluid dynamics. The ventilation effectiveness concept has been studied both concerning mixing ventilation and displacement ventilation, and many surprising situations with unexpected concentration levels have been identified in different situations. We have been involved in research work on transport processes for volatile organic compounds (VOC's) through participation in the Danish research programme "Healthy Buildings". This work involves both the emission process at a surface, convection and diffusion and personal exposure, as well as a study of a person as emission source. The results have improved the understanding of evaporation controlled emission in a room, and detailed models for the exposure process have been obtained by experiments with a breathing thermal manikin and CFD simulation. The "Healthy Building" programme has considerably strengthened the cooperation of the Indoor Environmental Group with other important national research teams. The programme has also opened up the prospects of an international cooperation with the European Commission Joint Research Centre in Italy and The University of Illinois at Urbane-Champaign in USA.

Research work on **Computational Fluid Dynamics** has increased during the evaluation period. Most of the work on CFD has been concentrated directly on improvements of software in connection with indoor environmental problems. New subroutines for the simulation of a diffuser have improved the prediction of the velocity level considerably, and work on damping functions in turbulence has been used to improve the predictions of displacement ventilation. The use of CFD in research work has reached a very high level in the end of the evaluation period, and projects as Large Enclosures, Healthy Buildings and Ventilation of Livestock Buildings are, to a great extent, based on this method.

The influence of the outdoor climate and external contaminant sources on the indoor environment in buildings was defined as a topic for new research unit in the 1989 long term research plan. It was not possible to obtain sufficient capacity to do any research during the evaluation period.

Research activities within the areas of **Control strategies and energy conservation in buildings** have shown the importance of multidirectional heat flow models. These models give a heat flow in closer agreement with experiments than the traditionally used one-dimensional heat flow models. A two-zone room model has also been developed to be used in connection with dynamic energy consumption programmes, and a programme modified with this model is able to calculate the temperature gradient in the room as well as air temperatures and surface temperatures.

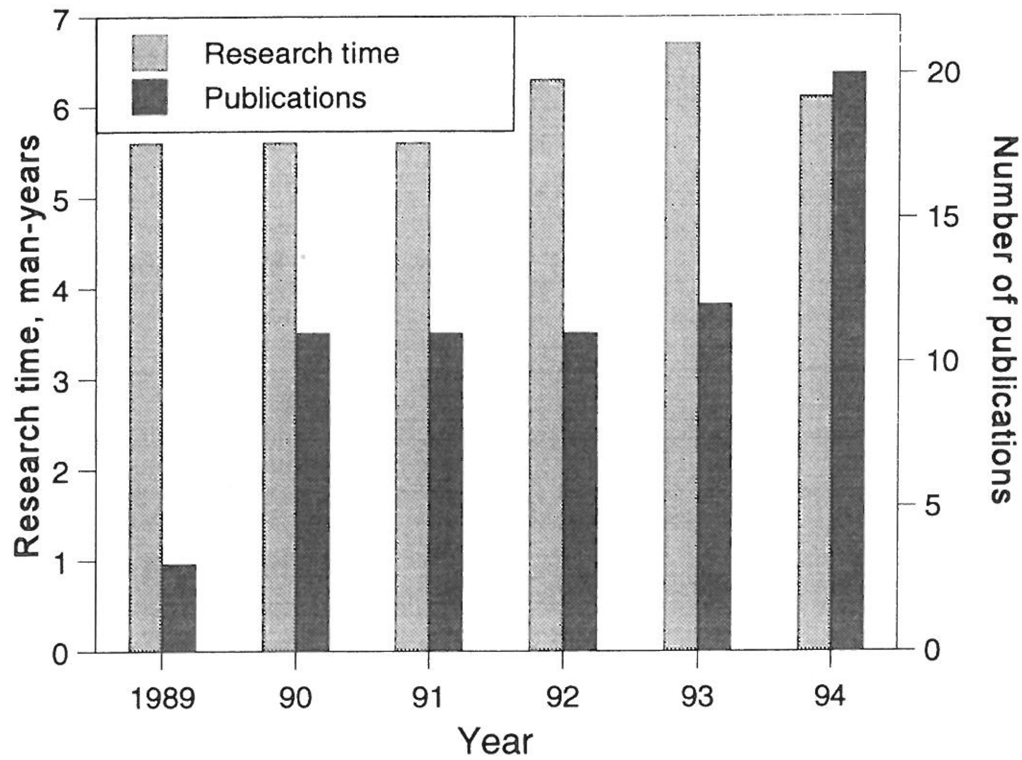

Figure 3.4 The available research time in research years and the number of publications produced each year.

The increase in research activities has also been reflected in the number of publications, which have been strongly increased, although the number of research years available has shown a much less increase, as shown in figure 3.4. The number of publications per research year has increased from 0.5 to 3.3 with an average of 1.9 in the evaluation period. The Indoor Environmental Group has given high priority to an improved quality of its publications and to an establishment of a publishing policy. This has resulted in an increasing number of reviewed publications during the last years as shown in figure 3.5.

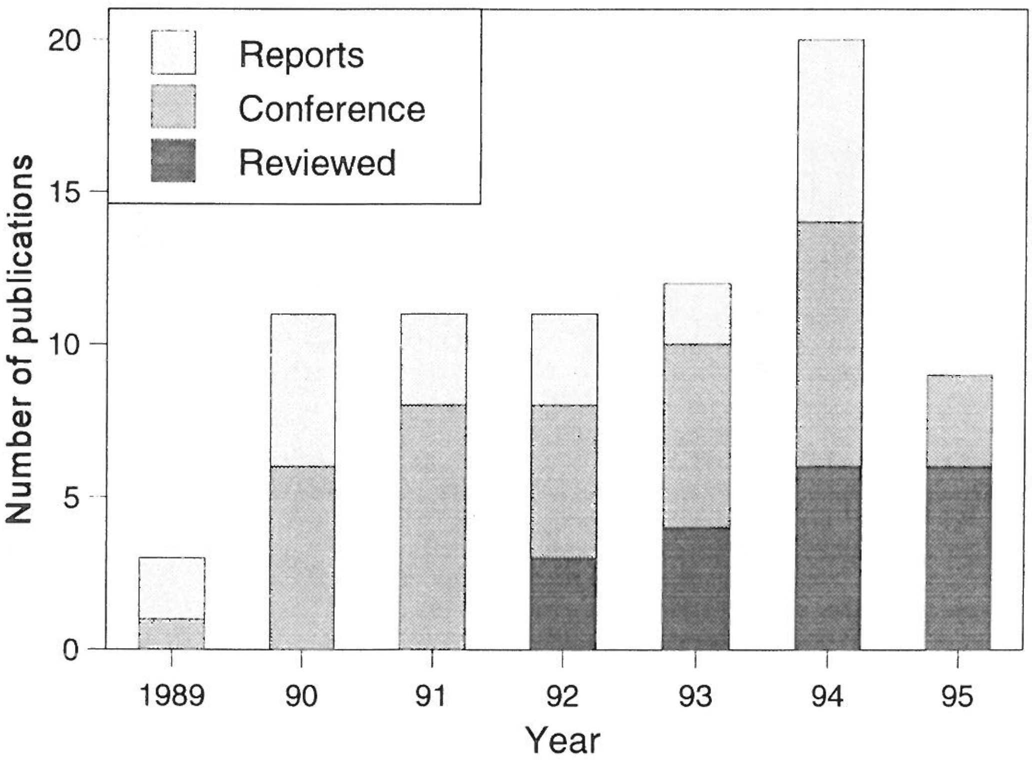

Figure 3.5 The number of publications during the evaluation period. The types of publications are explained in chapter 5. The column for 1995 indicates future publications known by December 1994.

Resources allocated to the group

The Indoor Environmental Group has during the evaluation period been able to slightly increase the available research time per year, see table 2.1. However, the funding of the research time has changed dramatically, see figure 3.6. The university funded research time has decreased by approx. 30% from 4.0 research man-years in 1989 to 2.8 research man-years in 1994. This has mainly been due to an increase in the Group's teaching and administrative duties. To compensate for this the Indoor Environmental Group has managed to increase the externally funded research time from 1.6 research man-years in 1989 to 3.3 research man-years in 1994.

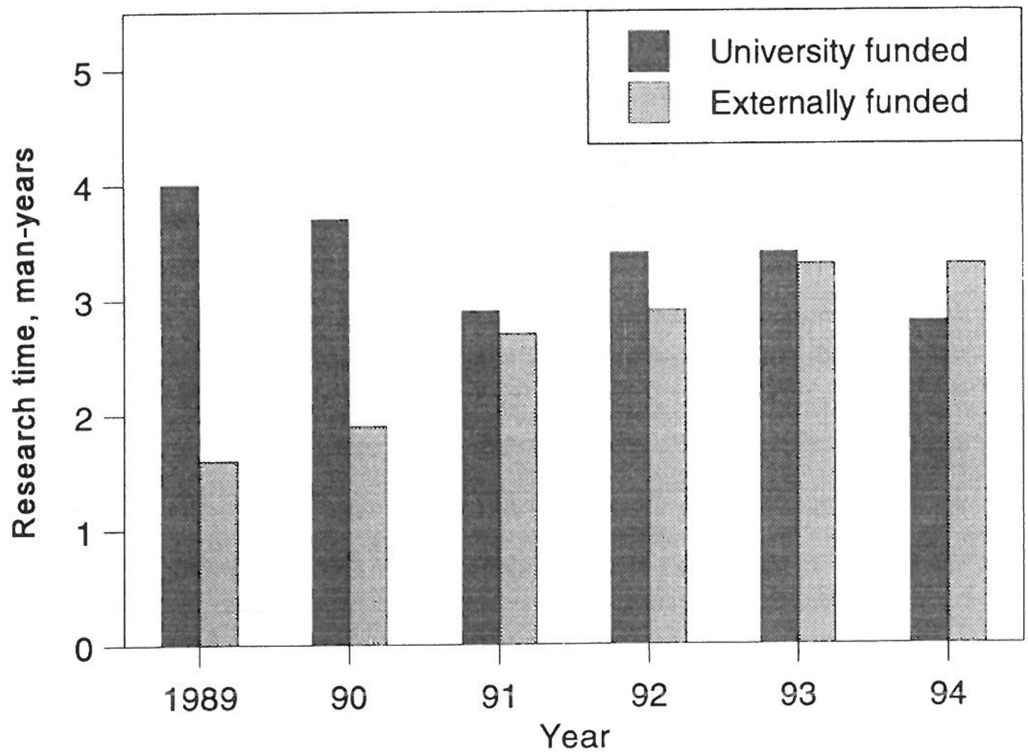

Figure 3.6 Research time in years funded by the university and by external funding during the evaluation period 1989 - 1994.

During the evaluation period the Indoor Environmental Group has been able to increase the external funding of research from approx. 0.3 million DKK per year in 1989 to 1.1 million DKK per year in 1994 and, as it can be seen on figure 3.7, the external funding will be progressing in the coming years. The external funding has been very important to the research in the Indoor Environmental Group and it has made it possible to maintain and slightly increase the activity level in spite of the decreasing funding from the University.

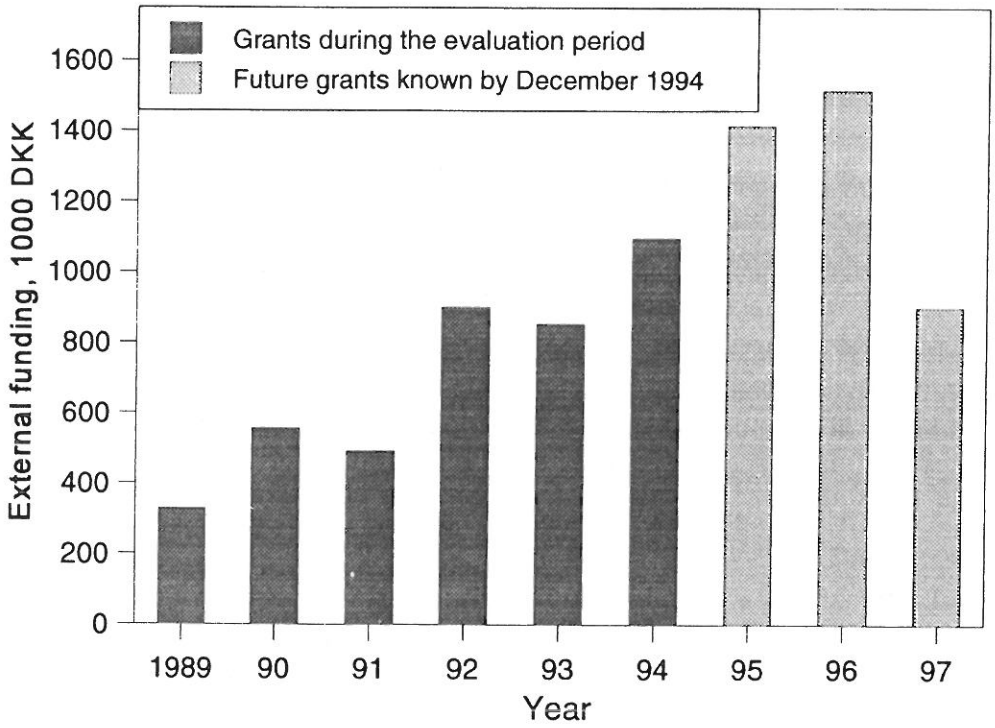

Figure 3.7 The external funding during the evaluation period and future grants known by December 1994.

Laboratories and equipment

The development in the research activities throughout the evaluation period and the changing demands for full-scale tests have required new laboratory facilities. The extension of the Indoor Environmental laboratory (two new full-scale test rooms complete with equipment) has ensured that the laboratory meets the new demands. For the next few years an enlargement of the laboratory will not be needed, but the current development of the test rooms and of the equipment will be continued to ensure that the laboratory permanently will live up to the research demands. The available hardware and software for the Computational Fluid Dynamics (CFD) calculations in the research projects have been adequate in the evaluation period. The development in the use of CFD in research projects during the last part of the evaluation period and in the future will, however, demand investments in both hardware and software. Advanced programmes to energy simulation of buildings and HVAC systems will also be needed in the future when the field of special effort regarding Models and Control Strategies for Energy Consumption in Buildings will be given a higher priority.

3.4 Future plans

The Indoor Environmental Group will work for a reasonable growth of external funding in the years to come. This will enable the group to increase the research activities in accordance with increasing experience, and it will stabilize the recruitment of researchers.

The research group will continue the publication policy which started in this evaluation period. The number of reviewed papers will be increased, and the tendency of an increasing number of publications per research man-year, from the level of 3.3 achieved in 1994, will be maintained.

The research activities during the evaluation period have been on different levels. Some pieces of work were applied research for Danish companies, and others, as for example parts of the Healthy Building Programme, have been research work with advanced models which has a 5 to 10 years' development time before the industry can utilize the research results, see figure 3.8.

The research work for the coming years will also have different levels. The group will work for research contracts with a short development time, but a large part of the research will be strategic research towards basic research with a longer development time. The Indoor Environmental Group will support the industry and other interested groups by arranging seminars, participation in congresses and symposia in order to inform of the research activities on all levels.

We expect to continue the work on contaminant transport within the indoor environment This work is very important for the Indoor Environmental Group because sick building syndrome (air quality) is one of the very great problems within our research areas. The work has to take place as a cooperation between national and international groups, and this cooperation has a very positive effect on the communication of our research activities. Our work within this area will especially deal with the transport processes of VOC and particles from emission at surfaces to the personal exposure. Unsteady processes as, for example, absorption, desorption, unsteady load, start and stop of ventilation equipment, etc., will be considered. It is our intention to work with models at the level of applied research, as well as models which have a long development time, typical for strategic research and basic research.

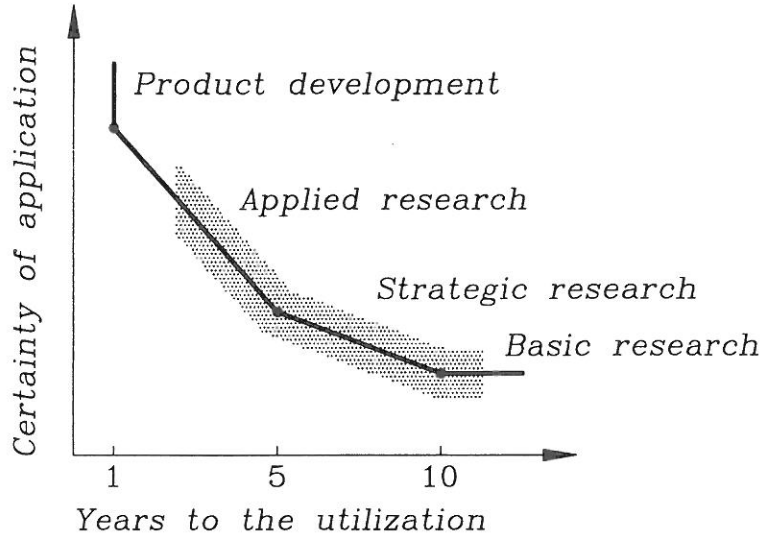

Figure 3.8 Certainty of application versus years to the utilization of research work. The areas for the Indoor Environmental Group are indicated in the figure.

The work on fundamental problems within mixing ventilation and displacement ventilation will be reduced because many basic problems have been addressed sufficiently during this evaluation period, and the attention will be directed to advanced problems in the application of mixing ventilation and displacement ventilation.

Industrial Ventilation, Ventilation in Livestock Buildings and Efficient Ventilation of Large Enclosures are research areas which have advanced ventilation problems. The research on Industrial Ventilation will be directed towards capture efficiency of local ventilation and the personal exposure in the working areas. The experiments and the simulations will both be made with tracer gas and particles. The heat load from the animals in livestock buildings is very high, and the occupational zone is large compared with the whole room volume. Therefore, it is important to make new research work on the simulation of the occupied zone in livestock buildings for an efficient use of CFD predictions. This work will also be extended to include the simulation of the occupied zone in other types of ventilated rooms. The work on efficient ventilation of Large Enclosures will continue, and the Indoor Environmental Group will be engaged in obtaining research contracts in cooperation with consulting engineers which deal with advanced problems in connection with air movement in large enclosures as atria, shopping malls, etc..

New areas which can be based on the fundamental research made by the Indoor Environmental Group up to the present are, for example, fire ventilation and smoke movement where a large part of the theory is similar to the theory used in displacement ventilation. Smoke movements in tunnels could especially be an interesting field, because there will be an increasing use of tunnels and underground railway systems in Europe and in the rest of the world in the next few years.

The research work in full-scale rooms, scale model rooms and computer simulations is based on a steady situation without time dependence. The room air movement is in practice a time-dependent flow, and this effect is also considered as part of a new research programme for the coming years.

The Indoor Environmental Group has made a number of experiments and simulations on a thermal breathing manikin. It is the intention to expand this work to the study of the flow and contaminant transport in the air passages of a human being. This work must be made in cooperation with medical researchers, and it should be within the area of strategic research.

There is a strong need for detailed measurements to validate new development in computational fluid dynamics and other areas. The group will continue to use full-scale rooms and test equipment to create measurements which can fulfil this need for ourselves and other research teams for the validation of different theories and models.

The earlier proposed research unit: Influence of the outdoor climate and external contaminant sources on the indoor environment in buildings may be covered as a smaller research field in the future.

Chapter 4
Additional information

4.1 Research collaboration

Research collaboration has been established with several universities, research institutes and private companies. Formal collaboration has been established with eight institutions in the form of participation in national or international research programmes, exchange of staff for extended periods or collaboration that has led to joint publications. Four of these institutions are Danish.

The Danish Research Programme on Healthy Buildings involves research collaboration with:

- Laboratory of Heating and Air Conditioning, Technical University of Denmark.
- Energy and Indoor Climate Division, Danish Building Research Institute.
- Institute of Environmental and Occupational Medicine, University of Aarhus.
- Danish National Institute of Occupational Health, Copenhagen.

The Danish Research Programme on Air Movements in Livestock Buildings involves research collaboration with:

- The Royal Veterinary and Agricultural University, Copenhagen.

The two International Research Programmes *Annex 20: Air Flow Patterns within Buildings* and *Annex 26: Energy-Efficient Ventilation of Large Enclosures* initiated by the International Energy Agency involve collaboration with more than 30 research groups in 13 countries.

During their study PhD students have been stationed at the following research centres:

- Unternehmensbereich, SULZER Infra, Winterthur, Switzerland.
- Department of Mechanical Engineering, UMIST, University of Manchester, United Kingdom.
- Institute of Industrial Science, University of Tokyo, Japan.
- Institut National de Recherche et de Sécurité, INRS, Centre de Recherche, Vandoeuvre Cedex, France.

Collaboration with the following institutions has led to joint publications:

- Institute of Industrial Science, University of Tokyo, Japan
- The National Swedish Institute for Building Research, Gävle, Sweden.
- Unternehmensbereich, SULZER Infra, Winterthur, Switzerland.
- Division of Energy Technology, Danish Technological Institute, Aarhus.
- The Royal Veterinary and Agricultural University, Copenhagen.
- N & R Consult A/S, Copenhagen, Denmark
- Danish National Institute of Occupational Health, Copenhagen.
- Institut National de Recherche et de Sécurité, INRS, Centre de Recherche, Vandoeuvre Cedex, France.

There has been research and development collaboration with the following private companies in Denmark:

- KE-Safematic A/S, Vejen
- Nordfab A/S, Mariager
- Rambøll A/S, Virum
- N & R Consult A/S, Copenhagen
- Velterm A/S, Østbirk

4.2 Other research and development activities

Besides the research activities, which are mentioned earlier, orders are carried out in the indoor environmental laboratories for private companies and other institutions. The extent of the orders can be from one day to several months. Typical orders have been:

- Development of software programs for data processing
- Laboratory test of product development
- Development and construction of test equipment

Contracts with the involved companies involve certain terms preventing publication so the projects can not be described in details in the present publication.

Figure 4.1 Equipment developed by the Indoor Environmental Group, here being prepared for shipment to the client.

4.3 Completed PhD projects 1989-1994

Per Heiselberg:
Flow Conditions in Rooms with Mixing and Displacement Ventilation (in Danish), 1990. Supervisor: Professor Peter V. Nielsen. External evaluators: Professor Tor-Göran Malmström, KTH, Sweden and Laboratory Chief Jørgen Schmidt Madsen, Lindab Riscanco A/S.

Peter Kofoed:
Thermal Plumes in Ventilated Rooms, 1991. Supervisor: Professor Peter V. Nielsen. External evaluators: Professor Klaus Fitzner, University of Berlin, Germany and Manager Bo Andersen, Crone & Koch K/S, Charlottenlund, Denmark.

Michael Skovgaard:
Turbulent Flow in Rooms Ventilated by the Mixing Principle, 1992. Supervisor: Professor Peter V. Nielsen. External evaluators: Professor Erik Olsson, Chalmers University of Technology, Sweden and Manager Bo Andersen, Crone & Koch K/S, Charlottenlund, Denmark.

Heine Overby:
Vertical Temperature Gradients in Rooms with Free Convection (in Danish). Supervisor: Associate Professor Mogens Steen-Thøde. External evaluators: Professor Mats Sandberg, Royal Institute of Technology, Sweden and Senior Researcher Keld Johnsen, Danish Building Research Institute, Hørsholm.

Lars Germann:
REEXS - Reinforced Exhaust System (in Danish, Industrial PhD project), 1992. Supervisors: Professor Peter V. Nielsen, Chief Engineer Arne Pedersen and Chief Engineer Claus Bihlet, Nordfab A/S and Researcher Søren Stjernquist, Danish Technological Institute, Taastrup. External evaluators: Professor Lars Olander, The National Institute of Occupational Health, Sweden and Senior Researcher Niels Oluf Breum, The National Institute of Occupational Health, Denmark.

Torsten Vammen Jacobsen:
Airflow and Temperature Distribution in Rooms with Displacement Ventilation, 1993. Supervisor: Professor Peter V. Nielsen. External evaluators: Associate

Professor Dr. Alfred Moser, ETH, Zürich, Switzerland and Senior Researcher Niels Oluf Breum, The National Institute of Occupational Health, Denmark.

Ulla Madsen:
Numerical Prediction of Dispersion and Local Exhaust Capture of Gaseous and Particulate Contaminants in the Indoor Environment, 1994. Supervisors: Professor Peter V. Nielsen and Senior Researcher Niels Oluf Breum, The National Institute of Occupational Health, Denmark. External evaluators: Professor Lars Olander, The National Institute of Occupational Health, Sweden and Senior Researcher Ole Valbjørn, Danish Building Research Institute, Hørsholm.

4.4 Organization of meetings and conferences

During the evaluation period, the group has arranged a number of meetings and conferences. At some of the arrangements we have had the opportunity to present results of the group´s research activities. These arrangements are as follows:

- Indoor Environmental Technology at Aalborg University. Meeting for BST in Aalborg. February 7, 1989. Organizer: Professor Peter V. Nielsen.
- International Energy Agency, Annex 20: Air Flow Patterns within Buildings, Expert Meeting. Aalborg, May 30 - June 2, 1989. Organizer: Professor Peter V. Nielsen.
- Displacement Ventilation - Theory and Practical Applications. DANVAK - meeting at Aalborg University, November 8, 1990. Organizer: Professor Peter V. Nielsen and Associate Professor Per Heiselberg.
- Glasoverdækkede Bygninger og Integreret Byggeri. DANVAK - meeting at Aalborg University, February 27, 1991. Organizer: Professor Peter V. Nielsen.
- Indoor Environmental Laboratory at Aalborg University. DANVAK - meeting at Aalborg University, September 3, 1992. Organizer: Professor Peter V. Nielsen and Associate Professor Per Heiselberg.
- International Energy Agency, Annex 26: Energy-Efficient Ventilation of Large Enclosures, Kick Off Meeting. Aalborg, August 30 - September 1, 1992. Organizer: Associate Professor Per Heiselberg

- Nordic Conference for VVS Professors. Aalborg University, September 1, 1992. Organizer: Professor Peter V. Nielsen.
- ROOMVENT '92. Third International Conference on Air Distribution in Rooms. Aalborg, September 2-4, 1992. Chairman Professor Peter V. Nielsen.
- Nordic Ventilation Group (NVG) Workshop on Displacement Ventilation. Aalborg University, November 9, 1992. Organizer: Professor Peter V. Nielsen.
- Clean Room Ventilation. DANVAK - Meeting at Aalborg University, March 17, 1993. Organizer: Professor Peter V. Nielsen and Assistant Professor Heine Overby.
- Numerical Prediction of Air Quality and Thermal Environment. Workshop at INDOOR AIR '93, Helsinki, Finland, July 6, 1993. Organizer: Professor Peter V. Nielsen.
- Indoor Environmental Research at Aalborg University. DANVAK - Meeting at Aalborg University, November 24, 1993. Organizer: Associate Professor Per Heiselberg.

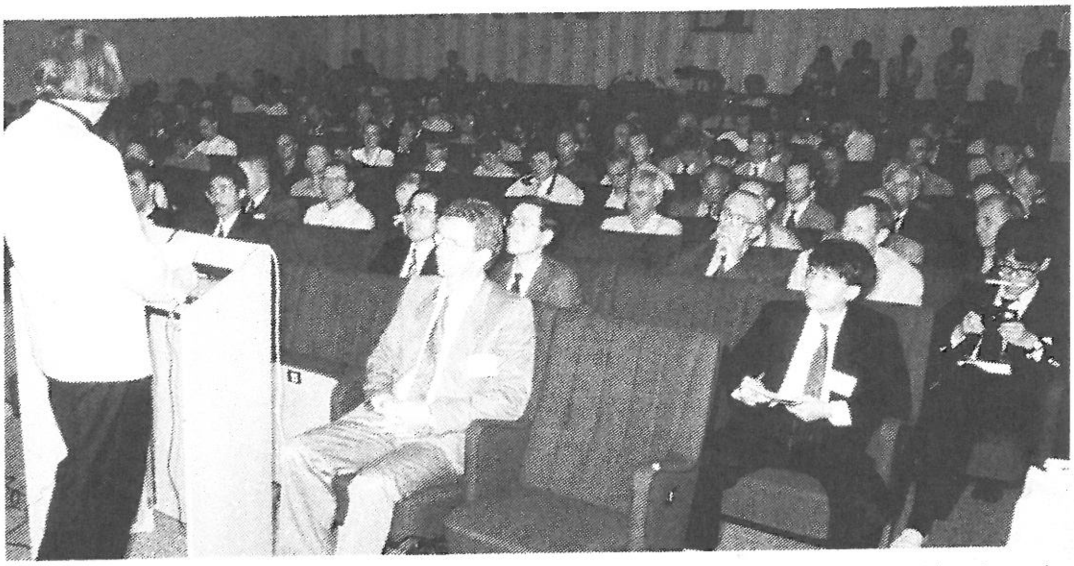

Figure 4.2 The Third International Conference on Air Distribution in Rooms, ROOMVENT'92 was held in Aalborg.

4.5 Staff by December 1994

University staff

Peter V. Nielsen	professor
Louis Evensen	professor
Carl Erik Hyldgård	associate professor
Thomas Pedersen	associate professor
Mogens Steen-Thøde	associate professor
Kjeld Svidt	research assistant professor
Henrik Brohus	PhD student
Erik Bjørn	PhD student
Torben Christensen	engineering assistant
Bodil Jensen	secretary
Bente Kjærgaard	secretary

Externally funded staff

Per Heiselberg	research associate professor
Gunnar P. Jensen	PhD student

4.6 Curricula vitae for the academic staff

Peter Vilhelm Nielsen

Born 4 April 1942

Education

1967 MSc in Mechanical Engineering, Technical University of Denmark.

1974 Lic. Techn. (PhD) in the subject "Flow in Air Conditioned Rooms", Department of Fluid Mechanics, Technical University of Denmark. This study is one of the first examples where prediction based on Computational Fluid Dynamics (CFD) is used in indoor environment.

Employment

1967-80 Central Research Department, Danfoss A/S, Denmark.

1976-77 Imperial College, London. Guest professor.

1980-82 Building Control Group, Danfoss A/S. Research manager.

1982-85 Building Control Group, Danfoss A/S. Division manager of Research and Development.

1985-86 Building Control Group, Danfoss A/S, Chief Engineer .

1986 Professor of Indoor Environmental Engineering, Department of Building Technology and Structural Engineering, Aalborg University.

Publications

116 publications. 23 of these are reviewed papers of which he is the first author of 16. 76 papers are published in international proceedings. About 50 national and international congress lectures. Peter V. Nielsen gives full courses or lectures that are arranged by Danish Society of Heating, Ventilating and Air-Conditioning Engineers (DANVAK), Koldkærgård Agricultural Centre, Danish Institute of Fire Technology, von Karman Institute for Fluid Dynamics and Nordic Academy for Advanced Studies.

Appointments

Peter V. Nielsen is a member of Commission E1, The International Institute of Refrigeration and has been a member of the Danish Technical Research Council, Commission B (1987-1993). He has been in the managing board of the Danish Building Research Institute (1988-1992). He is a member of the Danish Academy of Technical Science, a member of the Danish Working Environment Fund and has been a member of the National Folk University Board. He is an international member of the ASHRAE committee 5.3, Room Air Distribution, and member of the International Society of Indoor Air Quality and Climate (ISIAQ). He is a member of the managing board of the National Institute of Animal Science in Denmark and chairman of the External Test Group at Research Centre Bygholm. He is a reviewer for ASHRAE Transactions, Energy and Buildings, Building Services Research and Technology and various international conferences.

Peter V. Nielsen has participated in 3 committees for full professor appointments (2 Swedish and 1 Norwegian) and 5 PhD committees (3 Swedish and 2 Norwegian) as well as Danish Committees for associate professors and senior researchers. He was president of ROOMVENT '92, the third International Conference on Air Distribution in Rooms and has been in the advisory committees for ROOMVENT '87, Stockholm, ROOMVENT '90, Oslo, ISRACVE, Tokyo, 1992, ROOMVENT '94, Cracow, as well as ROOMVENT '96 in Yokohama. He has given lectures on CFD at the von Karman Institute for Fluid Dynamics, Belgium, and at the Nordic Research Education Academy.

Peter V. Nielsen has been a consultant for the Danish Supreme Court concerning questions on air distribution in rooms. He holds 9 international patents for oil burners and air terminal devices.

Awards

In 1990 Peter V. Nielsen received the Rockwool-prize for outstanding work on displacement ventilation and in 1992 he received the SCANVAC Award for outstanding work on heating and ventilation.

Louis Evensen

Born 26 June 1930

Education

1955 MSc in Mechanical Engineering, Technical University of Denmark

Employment

1957 Danish Building Research Institute in Copenhagen

1960 Patent Department, F. L. Smidth & Co., Denmark

1962 Engineering Academy of Denmark, Copenhagen and Aalborg

1974 Professor of Heating and Air Conditioning of Buildings at the Department of Building Technology and Structural Engineering, Aalborg University

Appointments

Member of the energy and environmental data association in Denmark: *Energi- og Miljødata* in Aalborg.

Carl Erik Hyldgård

Born 25 October 1942

Education

1967 BSc in Mechanical Engineering, Technical University of Denmark.

Employment

1967-69 Military service in the Danish Air Force.

1969-70 De Smithske, Aalborg.

1970-74 Assistant Professor in Indoor Environmental Engineering, Engineering Academy of Denmark, Aalborg.

1974- Associate Professor in Indoor Environmental Engineering, Department of Building Technology and Structural Engineering, Aalborg University.

Publications
13 publications. 4 papers are published in international proceedings. 3 international congress lectures.

Appointments
Carl Erik Hyldgård is the leader of the Indoor Environmental Laboratory, which has been built up during the years after 1975. He is responsible for purchase, calibration and maintenance of the measuring equipment. He is also developing and constructing new equipment for the laboratory such as full-scale test chambers, calibration equipment and measuring equipment. He is doing ordered work in the laboratory in form of examinations and special constructions.

Thomas Pedersen

Born 17 February 1938

Education

1959 BSc in Civil Engineering, College of Engineering, Horsens, Denmark.

Employment

1959-61	Military service in the Danish army.
1961-64	Dansk Arkitekt & Ingeniørkontor af 1945, Silkeborg, Denmark
1964-71	Studstrup og Østgård, Consulting Engineers, Aalborg, Denmark
1971-74	Aalborg College of Engineering, Denmark
1974-	Associate Professor in indoor environmental engineering, Department of Building Technology and Structural Engineering, Aalborg University

Publications
19 publications. 11 of these are used in connection with courses that are arranged by Aalborg University. Other publications deal with description of computer software and hardware for the engineering educations. Furthermore, some of the publications describe new educations in Fire Safety Engineering and Environmentally Compatible Building Arrangements.

Appointments
Thomas Pedersen is a member of the national network for Life-Cycle Assessment. All departments of Building Technology in Denmark are represented in this work.

Mogens Steen-Thøde

Born 7 December 1944

Education

1968 BSc in Civil and Structural Engineering, Engineering Academy of Denmark.

Employment

1969-74 Assistant Professor in Indoor Environmental Engineering, Engineering Academy of Denmark, Aalborg

1974- Associate Professor in Indoor Environmental Engineering, Department of Building Technology and Structural Engineering, Aalborg University.

1981-82 Consulting engineer and researcher, The Jutland Institute of Technology.

Appointments
Mogens Steen-Thøde is the chairman of the Study Board for Building Technology and Structural Engineering at Aalborg University. Member of the Danish Society of Heating, Ventilating and Air-Conditioning Engineers.

Kjeld Svidt

Born 10 September 1958

Education

1987 MSc in Agricultural Engineering, Royal Veterinary and Agricultural University, Copenhagen

1991 PhD in Agricultural Engineering, Royal Veterinary and Agricultural University, Copenhagen

Employment

1987-88 Research Assistant at the Department of Animal Science and Animal Health, The Royal Veterinary and Agricultural University, Copenhagen

1988-91 PhD student at the Department of Animal Science and Animal Health, The Royal Veterinary and Agricultural University, Copenhagen.

1991-94 Research Assistant Professor at the Royal Veterinary and Agricultural University. Stationed at the Department of Building Technology and Structural Engineering, Aalborg University.

1994- Research Assistant Professor at the Department of Building Technology and Structural Engineering, Aalborg University.

Publications

9 publications. 1 of these is a reviewed paper of which he is also the first author. 3 papers are published in international proceedings.10 national and international congress lectures.

Appointments

Kjeld Svidt is a member of the American Society of Agricultural Engineers, The Scandinavian Association of Agricultural Engineers and the Danish Society of Heating, Ventilating and Air-Conditioning Engineers. He has been a co-chairman at the ROOMVENT conference.

Henrik Brohus
Born 13 January 1967

Education
1992 MSc in Indoor Environmental Technology, Department of Building Technology and Structural Engineering, Aalborg University.

Employment
1992 PhD student, Department of Building Technology and Structural Engineering, Aalborg University.
1995 Visiting Research Associate (January - February) at the Laboratory of Heating and Air Conditioning, Technical University of Denmark.

Publications
6 publications. 3 papers are published in international proceedings. 10 national and international congress lectures.

Appointments
Henrik Brohus is a member of the board of the chapter of North Jutland of the Danish Society of Heating, Ventilating and Air-Conditioning Engineers.

Erik Bjørn
Born 30 September 1964

Education
1994 MSc in Indoor Environmental Technology, Aalborg University.

Employment
1994 PhD student, Department of Building Technology and Structural Engineering, Aalborg University

Publications
Two publications (one as first author) which will be published in international proceedings in 1995. One national congress lecture.

Appointments

Erik Bjørn is a representative of FYF, the PhD student organisation at Aalborg University. He is a member of the Danish Society of Heating, Ventilating and Air-Conditioning Engineers.

Per Kvols Heiselberg

Born 20 March 1962

Education

1986 MSc in Indoor Environmental Technology, Aalborg University.

1990 PhD in Indoor Environmental Technology, Department of Building Technology and Structural Engineering, Aalborg University.

Employment

1986 PhD student, Department of Building Technology and Structural Engineering, Aalborg University.

1988 Visiting Research Associate (January-May) at The National Swedish Institute for Building Research, Gävle, Sweden.

1989- Assistant Professor, Research Associate and Research Associate Professor, Department of Building Technology and Structural Engineering, Aalborg University.

Publications

20 publications. 5 of these are reviewed papers of which he is also the first author. 9 papers are published in international proceedings. 25 national and international congress lectures.

Appointments

Per Heiselberg is the subtask leader of the externally funded international project IEA-ECB Annex26: Energy-efficient Ventilation of Large Enclosures. He is a reviewer of papers for the International Journal of Indoor Air Quality and Climate, INDOOR AIR. He has sat on 2 PhD committees, 1 Danish and 1 Swedish. He has worked in the organizing committee of the 3rd International Conference on Air Distribution in Rooms, ROOMVENT'92 and has been co-chairman at a number of ROOMVENT conferences. He is a member of the board of the Danish Society of Heating, Ventilating and Air-Conditioning Engineers and also a member of the board of the chapter for North Jutland.

Gunnar Peter Jensen

Born 19 April 1965

Education

1990 MSc in Environmental Engineering, Aalborg University.

Employment

1991-93 Hydraulic Modeller, National Rivers Authority - Thames Region, UK.

1993- PhD student, Department of Building Technology and Structural Engineering, Aalborg University.

Publications

3 publications. 1 paper is published in international proceedings.

Chapter 5
Publications after 1989

This chapter gives a list of the group's research publications during the evaluation period. It also includes future publications, i.e. publications that are submitted or accepted for publication in 1995. The list of publications is divided into six sections:

- Reviewed and invited papers
- Papers in proceedings
- Books and chapters in books
- PhD theses
- Reports
- Danish publications

The group has also produced a number of tuitional papers and books which are not presented in this list.

5.1 Reviewed and invited papers

Brohus, H., Nielsen, P.V.
Personal Exposure in Displacement Ventilated Rooms. Accepted for publication in Indoor Air. 1995 b.

Heiselberg, P. & Bergsøe, N. C.
Measurements of Contaminant Dispersion in Ventilated Rooms by a Passive Tracer Gas Technique. Proceedings of the International Symposium on Room Air Convection and Ventilation Effectiveness, ISRACVE, pp. 427-431, Tokyo, Japan. 1992.

Heiselberg, P.
Concentration Distribution in the Centre Plane of a Ventilated Room under Isothermal Conditions. Indoor Air 1993, 3:34-40. 1993 a.

Heiselberg, P.
Draught Risk from Cold Vertical Surfaces. Building and Environment, Vol. 29, No. 3, pp. 297-301. 1994 a.

Heiselberg, P.
Stratified Flow in Rooms with a Cold Vertical Wall. ASHRAE Transactions, Vol. 100, part 1, pp. 1155-1162. 1994 b.

Heiselberg, P., Overby, H., Bjørn, E.
Energy Efficient Measures to avoid Downdraft from Large Glazed Facades. Accepted for publication in ASHRAE Transactions of the Annual Meeting in San Diego. 1995.

Madsen, U., Breum, N.O., Nielsen, P.V.
A Numerical and Experimental Study of Local Exhaust Capture Efficiency. Ann. Occup. Hyg, Vol. 37, No. 6, pp. 593-605. 1993 b.

Madsen, U., Breum, N.O., Nielsen, P.V.
Local Exhaust Ventilation - A Numerical and Experimental Study of Capture Efficiency. Building and Environment. 1994.

Madsen, U., Fontaine, J.R., Nielsen, P.V., Aubertin, G., Breum, N.O., Nielsen, P.V.
A Numerical Study of Dispersion and Local Exhaust Capture of Aerosols Generated from a Variety of Sources and Air Flow Conditions. Submitted to American Industrial Hygiene Association Journal. 1995.

Nielsen, P.V.
Air Distribution Systems - Room Air Movement and Ventilation Effectiveness. Proceedings of the International Symposium on Room Air Convection and Ventilation Effectiveness, ISRACVE, Tokyo, Japan. 1992 a.

Nielsen, P.V.
Description of Supply Openings in Numerical Models for Room Air Distribution. ASHRAE Transactions, Vol. 98, Part 1. 1992 b.

Nielsen, P.V.
Stratified Flow in a Room with Displacement Ventilation and Wall Mounted Air Terminal Devices. ASHRAE Transactions, Vol. 100, Part 1. 1994 a.

Nielsen, P.V.
Air Distribution in Rooms - Research and Design Methods. Opening Lecture at ROOMVENT'94, Fourth International Conference on Air Distribution in Rooms, Cracow, Poland. 1994 d.

Nielsen, P.V.
Prospects for Computational Fluid Dynamics in Room Air and Contaminant Control. Proceedings of Ventilation '94, Fourth International Symposium on Ventilation for Contaminant Control, Stockholm, Sweden. 1994 e.

Nielsen, P.V.
Air Flow in a World Exhibition Pavilion studied by Scale Model Experiments and Computational Fluid Dynamics. Submitted to ASHRAE Transactions. 1995 a.

Nielsen, P.V.
Velocity Distribution in a Room with Displacement Ventilation and a Wall Mounted Air Terminal Device. Accepted for publication in Energy and Buildings. 1995 c.

Svidt, K.
Numerical Prediction of Buoyant Air Flow in Livestock Buildings. Proceedings of the Fourth International Livestock Environment Symposium, Coventry, England. 1993.

5.2 Papers in proceedings

Brohus, H.
Air Flow in a Room Ventilated after the Mixing Principle with an Obstacle Placed in the Occupied Zone. Proc. Fifth Nordic Seminar on Computational Mechanics, Aalborg University, Denmark. pp. 146-150. 1992.

Brohus, H., Nielsen, P.V.
Contaminant Distribution around Persons in Rooms Ventilated by Displacement Ventilation. Proceedings of ROOMVENT'94, Fourth International Conference on Air Distribution in Rooms, Cracow, Poland. Vol. 1 pp. 293-312. 1994 a.

Brohus, H., Nielsen, P.V.
Personal Exposure in a Ventilated Room with Concentration Gradients. Proceedings of Healthy Buildings '94, 3rd International Conference, Budapest, Hungary. Vol. 2 pp. 559-564. 1994 b.

Brohus, H., Nielsen, P.V.
Personal Exposure to Contaminant Sources in a Uniform Velocity Field. Proceedings of Healthy Buildings '95, Fourth International Conference on Healthy Buildings, Milano, Italy, 11-14 September. Vol. 3 pp. 1555-1560. 1995.

Christensen, K.S. (Svidt, K.)
Numerical Prediction of Airflow in a Room with Ceiling-Mounted Obstacles. Proceedings of ROOMVENT'92, Third International Conference on Air Distribution in Rooms, Aalborg, Denmark. 1992.

Fox, S.G. & Nielsen, P.V.
Model Experiments in 1990 and On-Site Validation in 1992 of the Air Movement in the Danish Pavilion in Seville. Proceedings of Indoor Air '93. The 6th International Conference on Indoor Air Quality and Climate, Helsinki, Finland. 1993.

Germann Pedersen, L., Nielsen, P.V.
Exhaust System Reinforced by Jet Flow. Proceedings of Ventilation '91, Cincinnati, Ohio. 1991.

Heiselberg, P., Sandberg, M.
Convection from a Slender Cylinder in a Ventilated Room. Proceedings of ROOMVENT'90, International Conference on Engineering Aero- and Thermodynamics of Ventilated Rooms, Oslo. 1990.

Heiselberg, P.
Concentration Distribution in a Ventilated Room under Isothermal Conditions. Proceedings of the 12th AIVC Conference on Air Movement and Ventilation Control within Buildings, Ottawa, Canada. 1991 a.

Heiselberg, P.
Dispersion of Contaminants in Indoor Climate. Proceedings of Lüftungsforschung für die Praxis, pp. 101-108 ETH, Zürich. 1992 a.

Heiselberg, P.
Draught Risk from Cold Vertical Surfaces. Proceedings of Indoor Air '93 The 6th International Conference on Indoor Air Quality and Climate, Vol. 5, pp. 229-234, Helsinki, Finland. 1993 b.

Heiselberg, P.
Interaction between Flow Elements in Large Enclosures. Proceedings of ROOMVENT'94, Fourth International Conference on Air Distribution in Rooms, Vol. 1, pp. 363-376, Cracow, Poland. 1994 c.

Heiselberg, P., Overby, H., Bjørn, E.
The Effect of Obstacles on the Boundary Layer Flow at a Vertical Surface. Special Topic Presentation at Forum. The 5th Expert Meeting in IEA Annex 26: "Energy Efficient Ventilation of Large Enclosures", Leamington Spa, UK. 1994.

Hyldgård, C.E.
Water Evaporation in Swimming Baths. Proceedings of ROOMVENT'90, International Conference on Engineering Aero- and Thermodynamics of Ventilated Rooms, Oslo. 1990.

Hyldgård, C.E.
Humans as a Source of Heat and Air Pollution. Proceedings of ROOMVENT'94, Fourth International Conference on Air Distribution in Rooms, Cracow, Poland. 1994 a.

Jacobsen, T.V. & Nielsen, P.V.
Velocity and Temperature Distribution in Flow from an Inlet Device in Rooms with Displacement Ventilation. Proceedings of ROOMVENT'92, Third International Conference on Air Distribution in Rooms, Aalborg, Denmark. 1992.

Jacobsen, T.V., Nielsen, P.V.
Numerical Modelling of Thermal Environment in a Displacement-Ventilated Room. Proceedings of Indoor Air '93 The 6th International Conference on Indoor Air Quality and Climate, Helsinki, Finland. 1993.

Jensen, G.P., Nielsen, P.V.
Transfer of Emission Test Data from Small Scale to Full Scale. Proceedings of Healthy Buildings '95, Milano, Italy. 1995.

Kofoed, P., Nielsen, P.V.
Thermal Plumes in Ventilated Rooms - Measurements in Stratified Surroundings and Analysis by Use of an Extrapolation Method. Proceedings of ROOMVENT'-90, International Conference on Engineering Aero- and Thermodynamics of Ventilated Rooms, Oslo. 1990.

Kofoed, P., Nielsen, P.V.
Thermal Plumes in Ventilated Rooms Vertical Volume Flux Influenced by Enclosing Walls. Proceedings of the 12th AIVC Conference on Air Movement and Ventilation Control within Buildings, Ottawa, Canada. 1991 b.

Kofoed, P., Nielsen, P.V.
Auftriebsströmungen verschiedener Wärmequellen - Einfluss der umgebenden Wände auf den geförderten Volumenstrom. Presented at DKV-Jahrestagung, Berlin. 1991 a.

Madsen, U., Breum, N.O. & Nielsen, P.V.
Local Exhaust Ventilation - a Numerical and Experimental Study of Capture Efficiency. Proceedings of Indoor Air '93 The 6th International Conference on Indoor Air Quality and Climate, Helsinki, Finland. 1993 a.

Madsen, U., Aubertin, G., Breum, N.O., Fontaine, J.R., Nielsen, P.V.
Tracer Gas Technique versus a Control Box Method for Estimating Direct Capture Efficiency of Exhaust Systems. Proceedings of Ventilation '94, Fourth International Symposium on Ventilation for Contaminant Control, Stockholm, Sweden. 1994.

Nielsen, P.V.
Airflow Simulation Techniques - Progress and Trends. Proceedings of the 10th AIVC Conference on Progress and Trends in Air Infiltration and Ventilation Research, Espoo, Finland, September 25-28. 1989 b.

Nielsen, P.V.
Models for the Prediction of Room Air Distribution. Proceedings of the 12th AIVC Conference on Air Movement and Ventilation Control within Buildings, Ottawa, Canada. 1991.

Nielsen, P.V., Madsen, U., Tveit, D.J.
Experiments on an Exhaust Hood for the Paint Industry. Proceedings of Ventilation '91, Cincinnati, Ohio. 1991.

Nielsen, P.V.
Velocity Distribution in the Flow from a Wall-mounted Diffuser in Rooms with Displacement Ventilation. Proceedings of ROOMVENT'92, Third International Conference on Air Distribution in Rooms, Aalborg, Denmark. 1992 c.

Nielsen, P.V., Murakami, S.
Numerical Prediction of Air Quality and Thermal Environment. Workshop Summaries, 6th International Conference on Indoor Air Quality and Climate, Indoor Air '93, Espoo, Finland. 1993.

Nielsen, P.V.
Model Experiments for the Determination of Airflow in Large Spaces. Proceedings of Indoor Air '93 The 6th International Conference on Indoor Air Quality and Climate, Helsinki, Finland. 1993 a.

Nielsen, P.V.
Healthy Buildings and Air Distribution in Rooms. Proceedings of Healthy Buildings '95, Fourth International Conference on Healthy Buildings, Milano, Italy, 11-14 September. 1995 d.

Nielsen, P.V.
Vertical Temperature Distribution in a Room with Displacement Ventilation. Presented at IEA, Annex 26, Energy Efficient Ventilation of Large Enclosures, Rome. 1995 e.

Overby, H., Steen-Thøde, M.
Calculation of Vertical Temperature Gradients in Heated Rooms. Proceedings of ROOMVENT'90, International Conference on Engineering Aero- and Thermodynamics of Ventilated Rooms, Oslo. 1990.

Overby, H.
Measurement and Calculation of Vertical Temperature Gradients in Rooms with Convective Flows. Proceedings of ROOMVENT'94, Fourth International Conference on Air Distribution in Rooms, Cracow, Poland. 1994.

Skovgaard, M., Nielsen, P.V.
Numerical Prediction of Air Distribution in Rooms with Ventilation of the Mixing Type using the Standard k,ε-Model. Proceedings of "Nordisk Indeklima - arbejdsmiljø og energikonference", Copenhagen. 1990.

Skovgaard, M., Hyldgård, C.E. & Nielsen, P.V.
High and Low Reynolds Number Measurements in a Room with an Impinging Isothermal Jet. Proceedings of ROOMVENT'90, International Conference on Engineering Aero- and Thermodynamics of Ventilated Rooms, Oslo. 1990.

Skovgaard, M., Nielsen, P.V.
Modelling Complex Inlet Geometries in CFD - Applied to Air Flow in Ventilated Rooms. Proceedings of the 12th AIVC Conference on Air Movement and Ventilation Control within Buildings, Ottawa, Canada. 1991 c.

Skovgaard, M., Nielsen, P.V.
Numerical Investigation of Transitional Flow over a Backward Facing Step using a Low Reynolds Number k,ε-Model. Proceedings of the 12th AIVC Conference on Air Movement and Ventilation Control within Buildings, Ottawa, Canada. 1991d.

Svidt, K.
Investigation of Inlet Boundary Conditions Numerical Prediction of Air Flow in Livestock Buildings. Proceedings of ROOMVENT'94, Fourth International Conference on Air Distribution in Rooms, Cracow, Poland. 1994 a.

5.3 Books or chapters in books

Heiselberg, P. & Nielsen, P.V.
Proceedings of ROOMVENT'92, Vol. 1-3. Danvak, Copenhagen. 1992.

Hyldgård, C.E.
Køleanlæg og varmepumper. Aalborg Universiy. 1993.

Nielsen, P.V.
Displacement Ventilation, Theory and Design. Aalborg University. 1993 c.

Nielsen, P.V.
Computational Fluid Dynamics in Ventilation. Aalborg University. 1994 c.

Nielsen, P.V.
Luftströmung in Raumen mit Mischlüftung. Chapter in the book: Technische Gebäudeausrüstung, Bauverlag, Wiesbaden, Germany. 1995 b.

Nielsen, P.V.
Luftströmung in Raumen mit Quellüftung. Chapter in the book: Technische Gebäudeausrüstung, Bauverlag, Wiesbaden, Germany. 1995 b.

Svidt, K.
Air Distribution in Livestock Buildings - Computer Calculation and Simple Methods (Luftfordeling i stalde - computerberegning og enkle metoder). The Royal Veterinary and Agricultural University and Aalborg University (in Danish). 1994 b.

5.4 PhD theses

Germann, L.
REEXS - Reinforced Exhaust System. Aalborg University. (In Danish). 1991.

Heiselberg, P.
Flow Conditions in Rooms with Mixing and Displacement Ventilation (Strømningsforhold i lokaler ventileret efter opblandings- og fortrængningsprincippet). Aalborg University. (In Danish). 1990.

Jacobsen, T.V.
Airflow and Temperature Distribution in Rooms with Displacement Ventilation. Aalborg University. 1993.

Kofoed, P.
Thermal Plumes in Ventilated Rooms. Aalborg University. 1991.

Madsen, U.
Numerical Prediction of Dispersion and Local Exhaust Capture of Gaseous and Particulate Contaminants in Indoor Environment. Aalborg University. 1994.

Overby, H.
Vertical Temperature Gradients in Rooms with Free Convection (Vertikale temperaturgradienter i rum med konvektive strømninger). Aalborg University. (In Danish). 1993.

Skovgaard, M.
Turbulent Flow in Rooms Ventilated by the Mixing Principle. Aalborg University. 1991.

5.5 Reports

Evensen, L.
Simulation of the temperature distribution in a brick wall (Simulering af temperaturforløb i teglstensydervæg). Aalborg University. (In Danish). 1989.

Evensen, L.
A Simulation Model for Dynamical Temperature Calculation in a Three-Dimensional Building Construction (Simuleringsmodel til dynamisk temperaturberegning for rumlig bygningskonstruktion). Aalborg University. (In Danish). 1990.

Evensen, L.
An Equation for the Heat Flux of a General Room Element (Effektbalanceligningen for det generelle rumelement). Aalborg University. (In Danish). 1990.

Evensen, L.
The Simulation Program GRIDNODE (Simuleringsprogrammet GRIDNODE). Aalborg University. (In Danish). 1992.

Heiselberg, P.
Measurements of Test Case F (Forced Convection, Isothermal with Contaminants), Research item 1.31. IEA Annex 20 Report, Aalborg University. 1991 b.

Heiselberg, P.
A Laboratory Study of the Contaminant Distribution in a Room (En laboratorieundersøgelse af forureningsfordelingen i et lokale). Working Report, Danish Energy Agency, 'Research Project: R17-32, Aalborg University. (In Danish). 1992 b.

Jacobsen, T.V., Nielsen, P.V.
Investigation of Air Flow in a Room with Displacement Ventilation by means of a CFD-Model. Aalborg University. 1994.

Lemaire, A.D., Chen, Q., Ewert, M., Heikkinen, J., Inard, C., Moser, A., Nielsen, P.V., Whittle, G.
Room Air And Contaminant Flow, Evaluation of Computational Methods, Subtask-1. Summary Report. International Energy Agency, Annex 20, TNO Building and Construction Research, Delft. 1993.

Nielsen, P.V.
Representation of Boundary Conditions at Supply Openings. IEA Annex 20 Report, Aalborg University. 1989 a.

Nielsen, P.V.
Specification of a Two-Dimensional Test Case. IEA Annex 20 Report, Aalborg University. 1990 c.

Nielsen, P.V.
Simulation of the Indoor Environment - Report from a Nordic seminar on Energy and Environment (Indeklimasimuleringer - Rapport over Nordisk energi- og miljøseminar). Copenhagen. (In Danish). 1990 b.

Nielsen, P.V.
Air Velocity along the Floor in a Room with Displacement Ventilation (Lufthastighed langs gulvet i et lokale med vægmonteret armatur og fortrængningsventilation). Presented at the annual meeting of the Nordic Ventilation Group, Oslo. (In Danish). 1990 a.

Nielsen, P.V.
Contaminating Processes and the General Ventilation (Forurenende processer - og den almene ventilation). Aalborg University. (In Danish). 1990 d.

Nielsen, P.V.
Computational Fluid Dynamics in Ventilation. Von Karman Institute for Fluid Dynamics, Belgium. 1993 b.

Nielsen, P.V.
Velocity Distribution in a Room with Displacement Ventilation and Low-Level Diffusers. IEA Annex 20 Report, Aalborg University. 1994 b.

Skovgaard, M., Nielsen, P.V.
Simulation of Test Case B (Isothermal Forced Convection). IEA Annex 20 Report, Aalborg University. 1991 a.

Skovgaard, M. & Nielsen, P.V.
Simulation of Simple Test Case, Case 2D1 (Two-Dimensional Isothermal Forced Convection). IEA Annex 20 Report, Aalborg University. 1991 b.

Steen-Thøde, M.
State-Space Representation of Transient Heat Transfer (Tilstandsbeskrivelse ved transiente varmestrømsproblemer). Aalborg University. (In Danish). 1989.

Steen-Thøde, M.
Numerical Calculation of Two-Dimensional Heat Transfer under Steady-State Conditions (Numerisk beregning af to-dimensional varmeledning under stationære forhold) . Aalborg University. (In Danish). 1992.

Steen-Thøde, M. (editor)
Building and Structural engineering at Aalborg University. Self Assessment Report. Aalborg University. 1993.

Steen-Thøde, M.
Program Package DYNTEMP. Simulation of One-Dimensional Transient Heat Transfer in Time and Frequency Domain (Programserie DYNTEMP. Dynamisk simulering og analyse af temperaturforhold i én-dimensionale konstruktioner). Aalborg University. (In Danish). 1994.

Steen-Thøde, M.
Program Package RADIATOR. Radiator Design and Analysis (Programserie RADIATOR. Dimensionering og analyse af driftsforhold for radiatorer). Aalborg University. (In Danish). 1994.

Steen-Thøde, M.
Program Package REGU. Dynamic Simulation of Heating Coil with Constant Fluid Flow (Programserie REGU. Dynamisk simulering af temperaturstyret varmeflade). Aalborg University. (In Danish). 1994.

5.6 Danish publications

Heiselberg, P., Sandberg, M.
Displacement Ventilation (Fortrængningsventilation - hvor standser fronten). VVS Denmark, Vol. 25, No. 6, Teknisk Forlag. (In Danish). 1989.

Heiselberg, P.
Downdraught and Draught (Kuldenedfald og Træk). VVS Denmark, Vol. 30, No. 8, Teknisk Forlag. (In Danish). 1994.

Heiselberg, P.
Well Insulated Windows Improve Thermal Comfort (Velisolerede vinduer forbedrer komforten). Glasmagasinet, Vol. 3, No. 4. (In Danish). 1994.

Nielsen, P.V., Brohus, H., Svidt, K., Jacobsen, T., Madsen, U.
Computer Calculation of Air Flow in Rooms (Computerberegning af luftstrømning i rum). VVS Denmark, Vol. 29, No. 10, Teknisk Forlag. (In Danish). 1993.

Nielsen, P.V.
Air Velocity in a Room with Displacement Ventilation (Lufthastigheder i et lokale med fortrængningsventilation). VVS Denmark, Vol. 30, No. 15, Teknisk Forlag. (In Danish). 1994 f.

Nielsen, P.V., Brohus, H., Heiselberg, P., Hyldgård, C.E., Jensen, G.P.
Healthy Buildings and Air Distribution in Rooms (Sunde bygninger og luftfordeling i rum). VVS Denmark, Vol. 31, No. 2, Teknisk Forlag. (In Danish). 1995.

Chapter 6
Report from the evaluation committee

6.1 Research evaluation guidelines

As stated in the guidelines for the research evaluation the purpose of the evaluation is to assess the quality of the research of the Indoor Environmental Group. The evaluation covers the following points:

- Research results published in internationally accepted journals or presented at internationally recognized conferences
- Other research results (not published traditionally but conveyed to the industry, public authorities etc. as well as Danish reports and publications)
- National and international research collaboration
- The progress of the research
- Other research activities, including arrangement of conferences, meetings and participation in symposia,

The aim of the evaluation is to assess whether there is a satisfactory agreement between allocated internal and external research resources and the research accomplished, and to advise the unit with respect to future efforts and the organization of the research.

6.4 Objectives and research accomplishment

Goals of 1989 for the years 1989-94

The long-term research plan of 1989 (chapter 1.3) concentrated on (1) Air flow and contaminant distribution, (2) Control strategies for energy consumption, and (3) Influence of outdoor climate on indoor climate.

The current evaluation confirms the progress in areas (1) and (2), including completion of several sub-projects and new solutions to many problems.

The efforts toward goal (3) received a lower priority because it was decided to concentrate attention to the first two objectives and because of limited resources.

Goals of 1994 for the years 1994-99

The future plans, chapter 3.4, contain a list of six research topics:

(1) Fire and smoke control
(2) Tunnel ventilation
(3) Time-dependent flow
(4) Contaminant transport processes, steady and unsteady, of VOC and particles
(5) Measurements and simulation of the thermal flow around the human body, using the breathing manikin, and extension to the transport processes in the human respiratory tract
(6) Experimental validation of numerical models of computational fluid dynamics

Research into a number of current application fields of high relevance will be continued:

(7) Industrial ventilation
(8) Ventilation of livestock buildings
(9) Ventilation of large enclosures
(10) Dynamic room models and design and control of HVAC systems

Research subjects

Eight subjects are listed in chapter 3.1. The topics are well chosen to cover the investigation of the physics of room air and contaminant flow, the development of ventilation systems in general, and the application to particular buildings and their use:

- Methods of analysis:
  - Convection flow in room air
  - Contaminant transport in the indoor environment
  - Numerical simulation of air distribution in rooms

- Methods of achieving ventilation goals:
  - Mixing ventilation
  - Displacement ventilation

- Application to specific building classes:
  - Industrial ventilation
  - Agricultural ventilation
  - Efficient ventilation of large enclosures

The results are well documented in publications and reports. The work is of an advanced standard and is relevant to today's industry needs and to the protection of human health and comfort.

Research accomplishments during the reporting period

The group has a remarkable output during the last six years, both in quality and volume (number of publications). The average productivity per person was above average, and the number of publications per staff member (research man-years, Figure 3.4) increased from 0.5 in 1989 to over 3 in 1994. Since 1992 there has been a significant increment in the number of peer-reviewed papers.

Active projects may be assigned to two classes: Development of methods to *analyse* air flow and contaminant distribution in rooms and *innovations*, i.e., invention and development of new concepts.

- Analysis:
  - Measurement in test rooms and on real buildings
  - Numerical simulation of indoor climate by computer (new models account for humidity, for damping of turbulence in stagnant flow, and for radiation)
  - Scale experiments
  - Lagrangian approach for particle tracking to predict capture efficiency of a local exhaust
- Innovation (the following list of inventions is not exhaustive):
  - Specification of a thermal breathing manikin to study the thermal flow around the body and details of inhalation and exhalation
  - Prescribed velocity method to specify boundary conditions at supply openings in CFD
  - Passive method to control downdraught on tall glazing by horizontal ledges
  - A calibration wind tunnel that can be rotated to determine the influence of gravity
  - Development of the flow element method for a simplified simulation of room air flow when several plumes, supply jets, and convective boundary layers coexist but do not interact
  - Scale-model experiments, and CFD predictions of an unconventional air conditioning system in the Danish Pavilion at the Seville World Exhibition of 1990

Observations and descriptions of new flow phenomena may also be listed under innovations:

- The low-frequency horizontal wandering of a thermal plume over a fixed heat source in an enclosure
- Development work on a local exhaust with aerodynamic control of the air flow
- The interaction of thermal plumes with stratified flow (new, extensive measurements). New results for plumes near walls that are based on the mirror principle
- New correlations for the radial gravity flow from a low-speed diffuser for supply of cool air

The large number of useful innovations demonstrate the creativity of the group and have contributed to its world-wide reputation.

6.5 Status and discussion

Resources

The four primary resources are: *Staff, money, time, equipment and facilities*. The evaluation shows a careful management of all resources.

Staff

The group comprises several researchers of high international reputation. The staff is the greatest asset and a prerequisite of outstanding work. The group has always attracted excellent students for PhD and other programs.

Money

Acquisition of external funding and grants has developed nicely, as seen in figure 3.7. An increase by a factor of over 3 between 1989 and 1994, and even by a factor over 4 to the projected figures for 1995 is remarkable. This is not only the result of good fund raising but also an unmistakable sign of confidence in the performance of the group by the funding agencies.

On the other hand, this good result should not induce the University to think, it could reduce its financial support of this group. On the contrary, the good record of the group and its scientific achievements should be rewarded by stronger support. And the external funding should be supplemented by contributions from the university. Figure 3.6 shows clearly that University funding (in terms of research time) decreased, on the average, during the reporting period. In 1989 external funding amounted to only about 30% of total research time, in 1994 this ratio increased to 54%. It is the evaluators' opinion that University support to research time should not drop below 50%.

Time

The management of time involves planning ahead. Good planning was behind the nice staggering of projects, as illustrated by Table 2.2. Different projects appear as overlapping "tiles" reaching as far as 1997, with a backlog of almost DKK 4 million at the end of the reporting period.

Seven PhD theses were completed during the period (chapter 4.3). Completion fell into 1990, 1991, 1992, 1992, 1993, 1993, and 1994. These projects are nicely spread in time which also suggests a good planning.

Although projects are overlapping, there are sometimes gaps in the support of individual persons. It is important, that the funding by the University is sufficient to bridge these gaps and to keep qualified young staff at the laboratory if new external financing is in sight.

Equipment and facilities

The evaluation confirmed that test facilities and instruments were only purchased with a clear purpose for its use. And then, a basic configuration of high quality equipment was selected. As an example, all the three full-scale test rooms are built in a way that allows easy modifications for individual projects. No attempts have been made to build sophisticated and overly expensive climatic chambers that would meet all known and unknown future requirements. Instead, parts of the test rooms are built in plywood to allow arbitrary installation of supply- and extract openings.

Measuring instruments are of highest standard, initially acquired for a particular project. But they are selected with future use in mind. All instruments are well kept and calibrated at least once a year, user manuals are accessible, and competent instruction is given to new students. All instruments are equipped with digital interfaces for networking with data acquisition computers, as appropriate.

Personal computers (PC) and two workstations (WS) are used for research purposes. Although the physical lifetime of a PC or WS may exceed 10 years, it should be kept in mind that operational lifetime for efficient use is 5 years or less. This is because hardware performance grows so rapidly, with new software constantly adjusted to the latest development, that it would be inefficient to work with obsolete equipment and impossible to compete in today's research community. Besides, students who enter industry after graduation should be up-to-date on latest developments. Therefore, sufficient funds should be assigned to the constant update of the computer fleet.

The research group should consider to buy commercial computer codes for certain advanced computing tasks. As these licenses are often expensive, the University should help to finance such projects and try to negotiate a site license. In this way, researchers and students of the whole University could use such packages. It is still useful if staff members write their own source code, – this is the best introduction into a computing problem. But these research codes are often not usable by other persons and for slightly different problems unless a comprehensive documentation is provided. The group should build on existing software and concentrate its efforts to improvement of established models or development of new models, that may be incorporated in commercial codes.

Products

To evaluate the performance of the laboratory, the products have to be examined:

(1) trained engineers, graduates (chapter 2.5)

(2) publications, theses, and reports (chapter 5)

(3) methods of analysis

(4) methods to achieve ventilation goals

The products of all four types are described in this booklet. In the evaluators' opinion they are all of high quality and in quantities that are impressive for the size of the group.

Performance-versus-cost assessment

The research accomplishment has been remarkable both in absolute terms and in comparison with the quite modest resources which have been available. Resources are carefully managed, investments in equipment are done in a prudent way. The productivity of the research group is above average.

6.6 Evaluation

Research strategy

The mix of projects with respect to depth and time-to-application is good (figure 3.8). Long-range basic research is cleverly combined with applied research and product development. The link to industry and practical engineering guarantees continued relevance of the research and a market for the research products.

Cooperation

Cooperation with other national and international research groups is excellent (chapter 4.1). A strong exchange program brings students from other countries to Aalborg, and permits Danish researchers to visit other laboratories, as, e.g., in France, Japan, Sweden, the UK, or the USA.

International cooperation is essential when numerical or experimental methods must be validated. This was accomplished, e.g., by participation in IEA projects. An important interdisciplinary cooperation has been established with four other Danish Institutes within the "Healthy Buildings Research Programme". It has provided a fruitful and productive collaboration with Danish indoor climate researchers within toxicology, chemistry and comfort.

Publicity and knowledge transfer

Attention must always be paid to good marketing and publicity. This was successfully done by organizing conferences (ROOMVENT'92) and post-graduate courses and by giving lectures at the von Karman Institute, VKI, in Belgium. Positive publicity is also achieved by staff members delivering invited lectures at international conferences. This happened several times. The active participation in scientific committees of conferences and the work as journal editors also add to publicity. The trend of increasing the number of publications in refereed international journals should be encouraged in the future. Efficient transfer of new knowledge to the engineering community, to designers and building operators should be kept up in the future. The "translation" of scientific results for the practitioner has a high priority, and to this end a number of short papers has been published in HVAC-engineering journals.

6.7 Recommendations

Future research

It is recommended that the future research is concentrated mainly on the fields where the group already has a strong international reputation. In particular transport processes, air distribution in spaces supported by CFD-modelling and experimental validation.

The work on transport processes in spaces provides a promising potential for modelling of transient pollution concentrations in line with the quickly developing characterization of pollution sources and sorption processes at surfaces.

The comprehensive experience on transport processes, air distribution and CFD should also be utilized in further research topics in other areas like:

- measurements and simulations of the thermal flow around the human body
- fire and smoke control

as well as for detailed development work in the area of:

- industrial ventilation
- ventilation of livestock buildings
- ventilation of large enclosures

In addition to collaboration with researchers within fluid dynamics, further interdisciplinary collaboration with scientists within other fields (toxicology, chemistry and comfort) could provide fruitful opportunities for future research.

Funding

Considering the high international reputation of this group, among the best in the world, the University should make sure to allocate proper resources to strengthen this field. A new permanent position as associate professor would be essential to maintain outstanding young talent in the group, and prepare a coming "generational change". The possibilities of further international funding should be explored, especially within the European Union.

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